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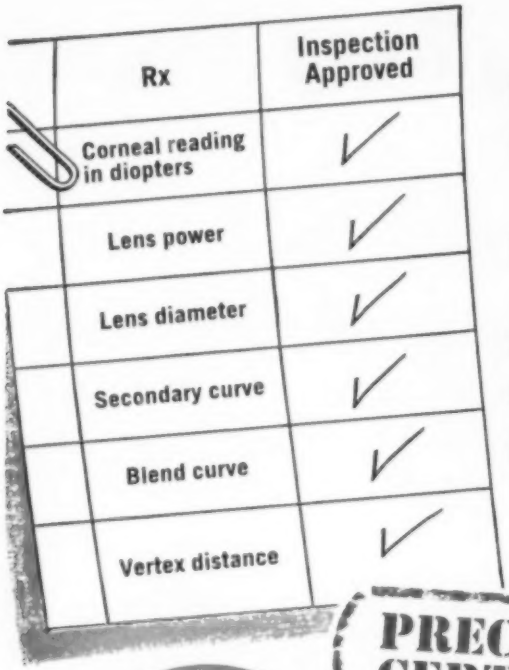


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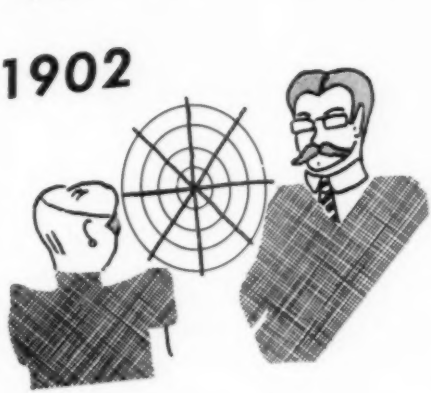


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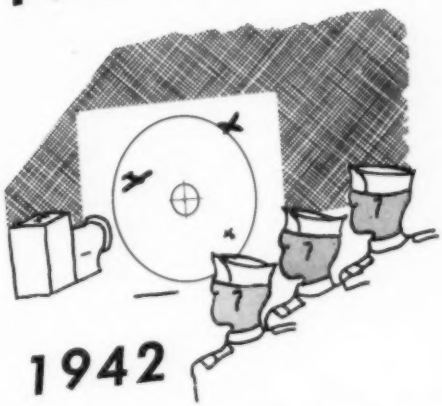


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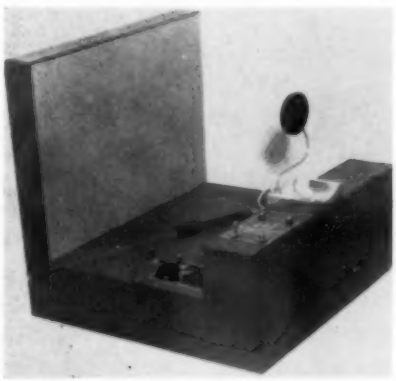

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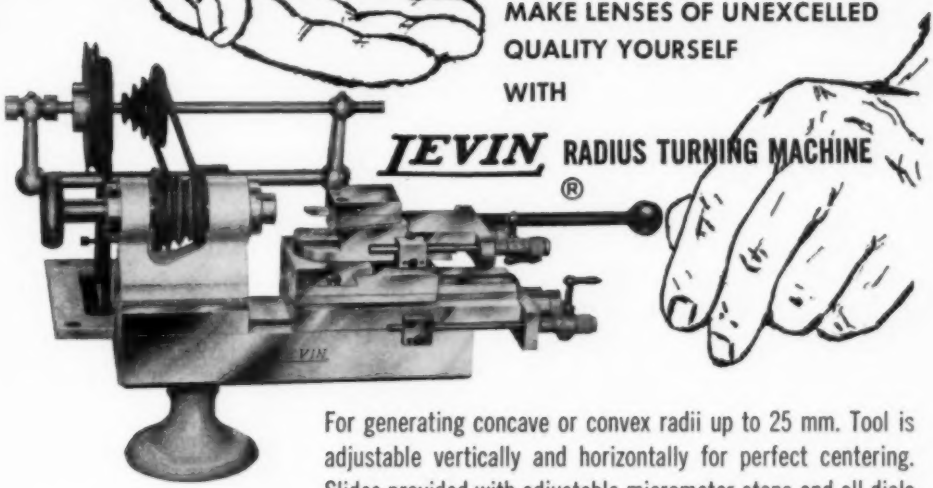

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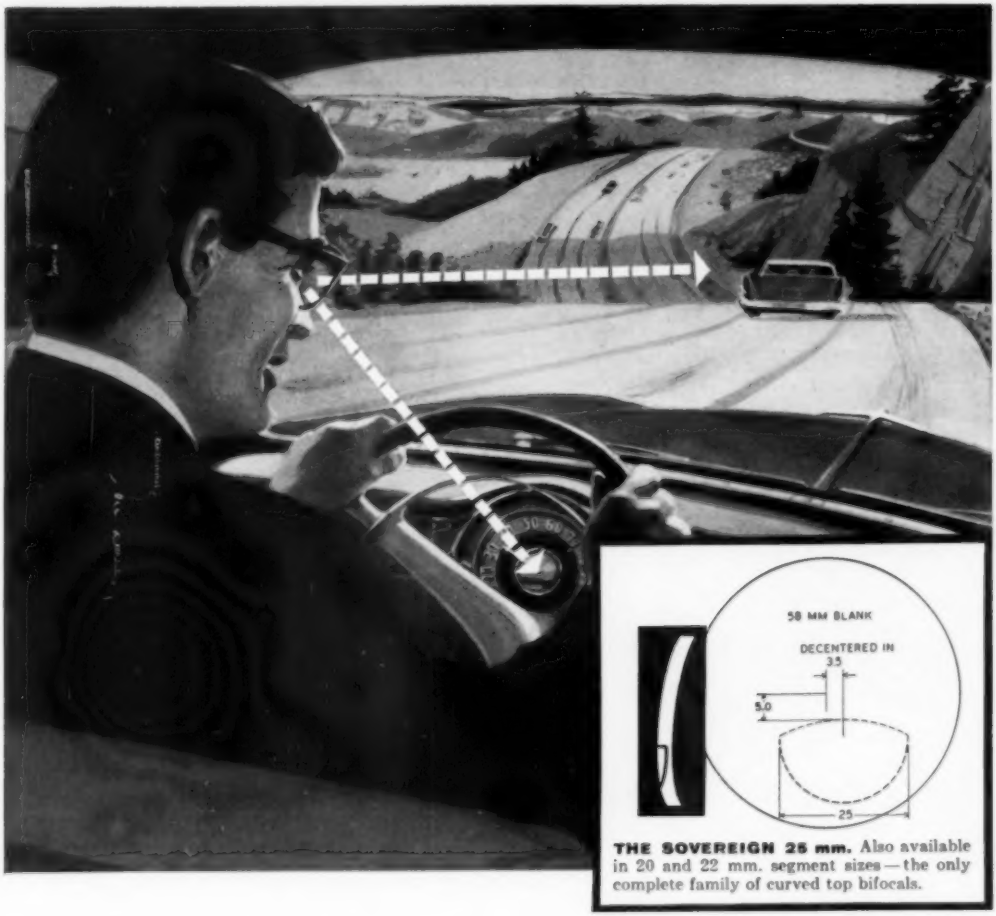


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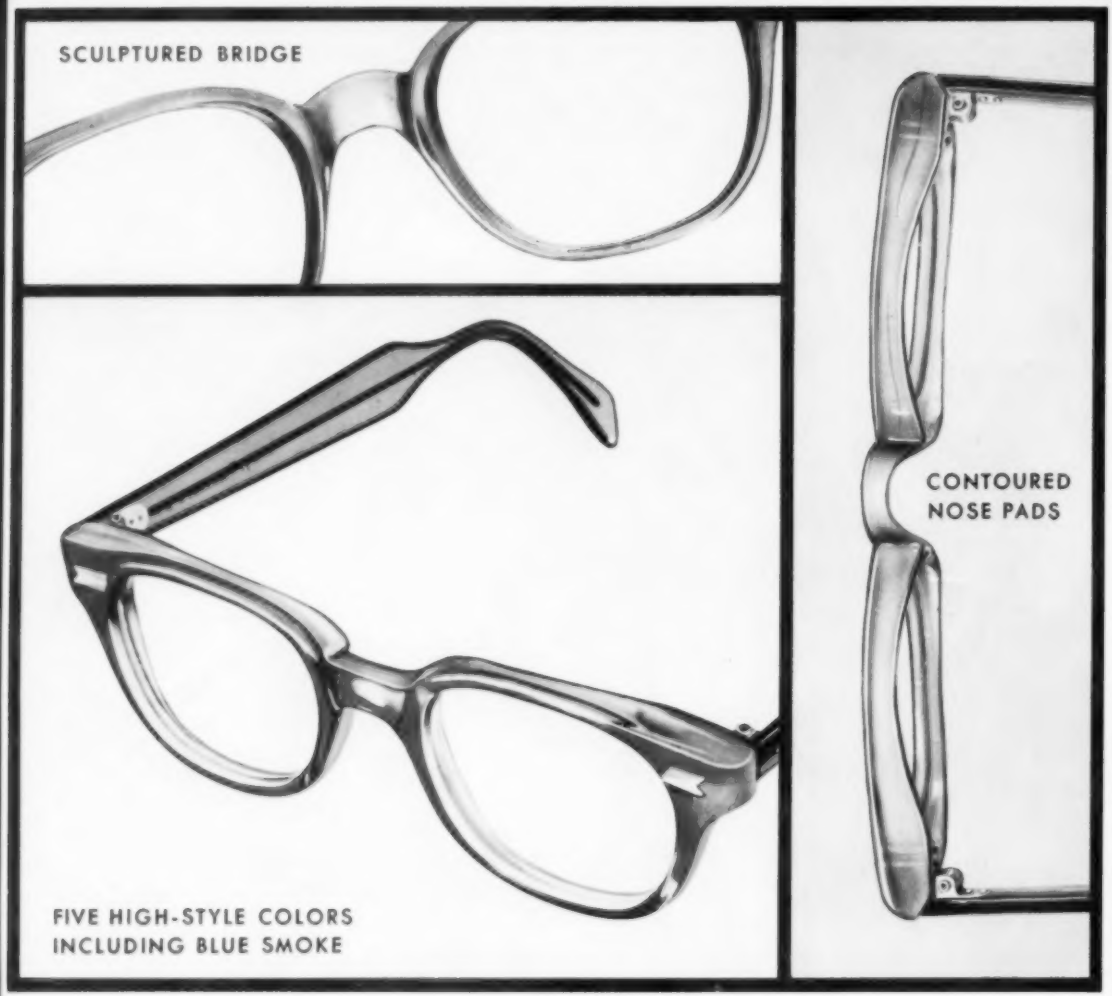


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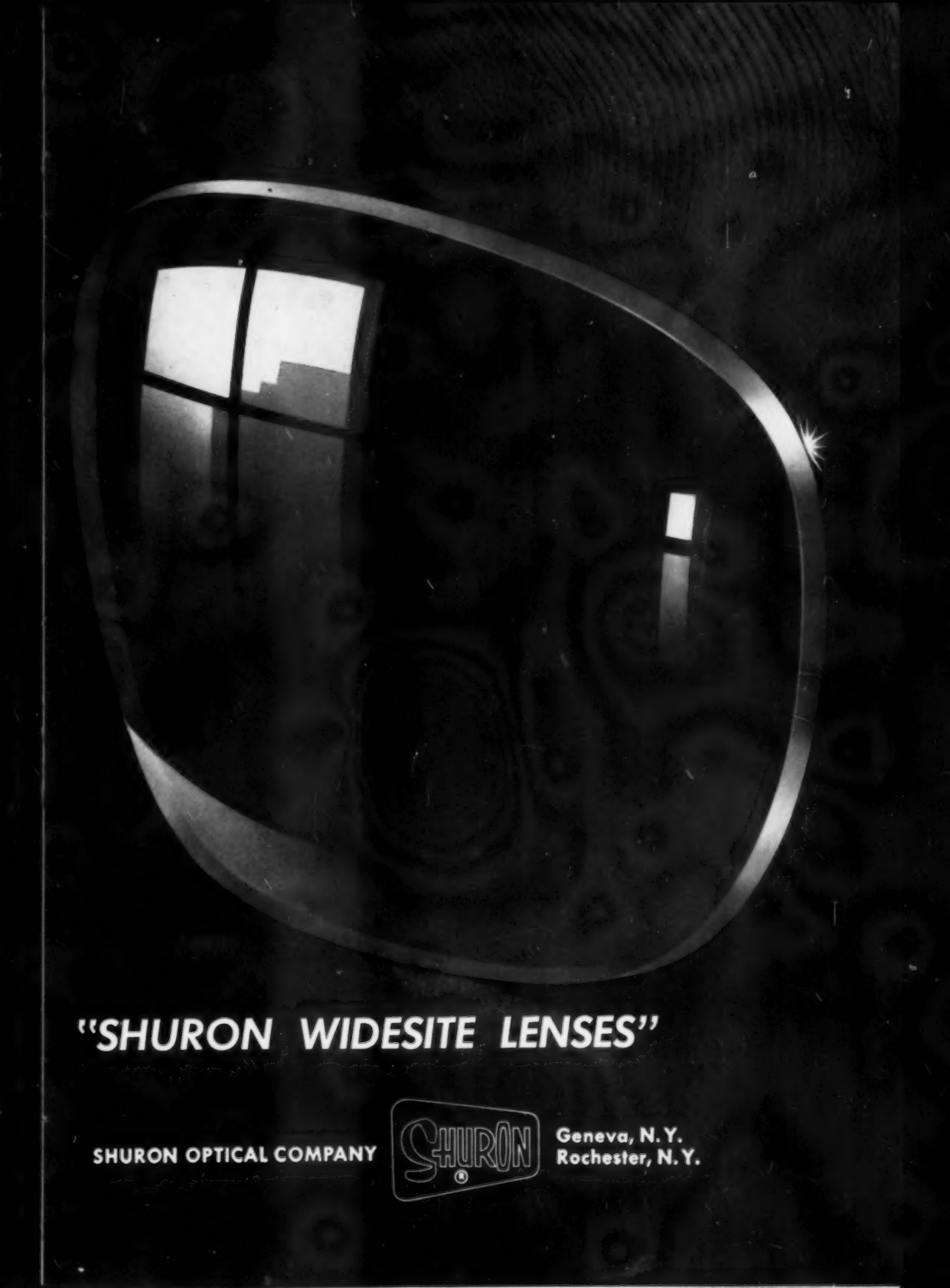
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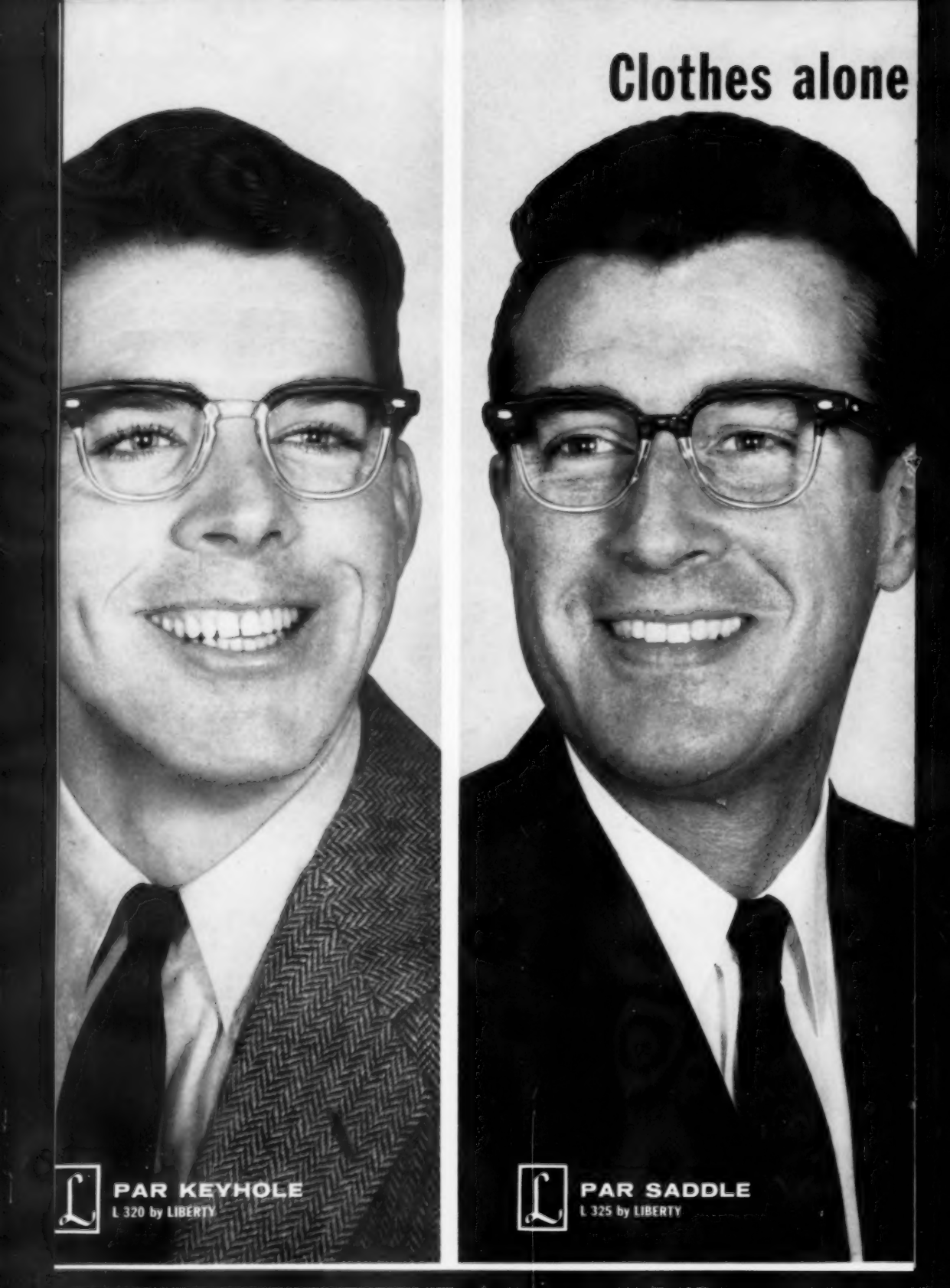
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AMERICAN JOURNAL OF OPTOMETRY
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Vol. 36 April, 1959 No. 4

# HOW GOOD IS THE H-R-R TEST FOR COLOR BLINDNESS?*

Gordon L. Walls†
School of Optometry, University of California
Berkeley, California

## INTRODUCTION

Pseudoisochromatic-chart tests for partial color blindness have been in use for many years. For separating defectives from normals, and for giving at least some indication of type and subtype of defect, they have always seemed cheap, and effective enough for purposes other than research. Testing devices that did any better job of differential diagnosis cost very much more; and, while a railroad or a paint factory did not wish to employ an applicant who was protanopic or deuteranopic, it didn't much care which defect he had.

These tests, whether devised in Germany, Japan, Sweden, France, Russia, or the United States, all work on the principle that if a character (usually a numeral) made up of variously-colored small spots is viewed on a background which is made up of spots also, the character will blend undetectibly into its background if the viewer is color-defective in such a way that the color sensations *he* gets from the various character-spots cover the same range as those *he* gets from the background-spots.

One or another chart test may depart a bit from this principle in some of its charts (like the Stilling test), or may embody a considerable elaboration on the basic principle (as does the Ishihara test). One test may separate protanoids pretty well from deuteranoids, while another tends to lump the protanomals and deuteranomals but sets them off quite sharply from the protanopes and deuteranopes (without distinguishing properly between them). Most chart tests make no pretense of catching "blue-yellow defectives," the uncommon tritanope and the extremely rare tetartanope and tritanomal. They are aimed at the far commoner "red-green defectives" who constitute about eight per cent of the male population and less than one-half percent of the female.

Most of the pseudoisochromatic tests ever made in this country

*Submitted on July 14, 1958, for publication in the April, 1959, issue of the AMERICAN JOURNAL OF OPTOMETRY AND ARCHIVES OF AMERICAN ACADEMY OF OPTOMETRY.
†Sc.D. Member of faculty. Fellow, American Academy of Optometry.

have been publications of the American Optical Company, commencing with the early wartime A.O. test, hastily compiled from 46 plates copied from among those in the suddenly unavailable Ishihara and Stilling tests (of respectively Japanese and German origin). Many plates whose combined presence made the test highly unsatisfactory were removed on the recommendation of Hardy, Rand, and Rittler,[1] to create a "revised selection" A.O. test. This was the first chart test for which the conditions of administration were properly rigid and fully spelled out. When the rules were strictly followed, the test failed very, very few normals and passed very, very few color-blinds. But it could serve *only* to separate normals from color-blinds when given by the usual examiner, who was not a researcher in the color-vision field. The average clinician could tell Mr. Jones that he was color blind, but not in what way, or how seriously.

The development of the A.O. H-R-R (for Hardy, Rand and Rittler) test was stimulated by the same dissatisfaction that led to the revision of the original A.O. Test. When it had been perfected, after a dozen years of experimentation and validation of handmade and privately printed prototypes and advance copies, it was published by the American Optical Company. Simultaneously, the company withdrew the 18-plate revised edition of its own eclectic test from the general civilian market, although the Armed Forces have chosen to continue in use a special version of that test, rather than train personnel to administer the H-R-R (which for their purposes is actually no better).

The commercial (A.O. Co.) H-R-R test was first published in 1955. In its earliest form the test was handmade, and was referred to by its designers as the "H-R-R Polychromatic Plates." These plates were eventually privately reproduced in limited numbers by special printing processes, for trial by chosen investigators and institutions. In this stage the plates were called a "second edition," and the designers referred to the forthcoming A.O. version as a "third edition." After the latter actually appeared with "pseudoisochromatic" substituted for "polychromatic" in the title, it was considered a first edition. There is now an A.O. second edition, issued in 1957, and the printed predecessor of the first A.O. version is now referred to as the "Prototype H-R-R." In the prototype, squares were used instead of the present triangles, and there were different numbers of plates in the different sections of the test. The plates in the 1957 "edition" are identical with those in the 1955, but two of them have been given a new location—the effect of which is to give red-green defectives six practise plates instead of four, and blue-yellow defectives four practise plates instead of eight.

The unimportant changes of procedure incorporated in the new manual could as well have been printed on the new record sheets (which are different from the 1955 score sheets, but no easier to get used to). It is hard to see why the "second edition" seemed necessary at all.

Most established refractionists who own a "revised A.O." test will probably use it until it is worn out. The new practitioner, equipping an office, finds that if he wants a pseudoisochromatic-chart test there are three that he can easily buy.

The Ishihara test is widely available in this country in a twelfth edition printed in Japan under Dr. Ishihara's supervision. It is the cheapest of the three,* and in the right hands it is an excellent normal-abnormal separator: but, the procedures for administering and scoring it have never been properly systematized and simplified. Only an expert can figure out how to use it to do as much as distinguish a protanoid from a deuteranoid.

Then, there is the second (1953) edition of the American-made Dvorine test. This can be made to work, as a normal-abnormal screen, as well as or better than the 18-plate selection A.O. (Newhall,[2] Peters[3, 4]). Moreover, it has been found to be as valid under the light from a cheap daylight fluorescent tube (6500° K) as under that from the expensive Macbeth Easel Lamp designed especially for use with pseudoisochromatic and other color-vision tests.[3, 4]

The H-R-R test offers more information about the defective testee than the 18-plate A.O., Ishihara, or Dvorine tests can be made to yield. Setting one's self up to use it, however, means paying out about twice as much for the test itself as for one of the others, and buying also the prescribed Macbeth lamp, which has not been shown to be indispensable. It is a good question whether the richer information is accurate enough to warrant the greater outlay. Most practitioners need only a screening test: but some, catering to the personnel of large local industries making colored products or (*e.g.*) in position to pass or fail applicants for police work, need to be able to discriminate among men who would be called "somehow color-blind" by any good screen—for, a few of these are salvageable for safe employment, and it may be tragic for them to be arbitrarily rejected.

The H-R-R test is unique in certain respects. The spots of different sizes and shades comprising the backgrounds are all neutral gray on all plates, so that the visual capacity required for reading the characters is

*The original 46-plate A.O. test can perhaps still be found, as an inexpensive "war surplus" item. It is easily converted into a revised selection by removing or covering up all but 18 particular plates.[1]

not hue discrimination but purity sensitivity. In the 14 plates intended to give trouble to red-green defectives, the spots in each character are all of some one hue out of a total of four, and each plate bears one character (an X, an O, or a Δ) or more often two, with one intended to be less discernible or undetectible by "protan" subjects, the other by "deutans." The colorimetric purities of the character-spots, hence the saturations of their colors for a normal observer, increase by steps as one progresses through the book.

Fewer plates are devoted to the detection and the qualitative and quantitative diagnosis of blue-yellow defectives. Here, each of six plates offers two characters, of hues chosen from a total of four, increasing in saturation from earlier plates to later ones, and with one character on each plate expected to be harder for a "tritan" to see, the other harder for a "tetartan."

Depending upon how soon the red-green defective stops making errors as he goes through the book, his defect is labeled "Mild R-G, unclassified as to type," or "Mild R-G," "Medium R-G," or "Strong R-G." A blue-yellow defective can only earn a "Mild B-Y, unclassified as to type," "Medium B-Y," or a "Strong B-Y" label. The particular errors that are made determine the protan-deutan and tritan-tetartan differentiations.

RED-GREEN DEFECTS: QUALITATIVE DIAGNOSIS

Let us consider the philosophy of these differences from other pseudoisochromatic-chart tests, first with regard to the red-green defects. The "strongest" of these defects are the dichromasies, protanopia and deuteranopia. For either the protanope or the deuteranope the spectrum contains only two hues, which decrease in saturation as they meet at a "neutral point" where, in a very narrow band of wavelengths, the light can be matched to a "white" light. The average protanope's neutral point, with respect to the light from a Macbeth Easel Lamp, is at λ492.3 mμ; the average deuteranope's, at 498.4 mμ (Walls and Heath[5]). These values are in the blue-green region, with the protanope's at a bluer blue-green and the deuteranope's at a greener blue-green. Should either dichromate view spots, the dominant wavelength of which is exactly the wavelength of his neutral point, he will not discriminate them from neutral gray spots of the same (for him) range of value or tone, irrespective of whether the purity of the chromatic spots is high, medium, or low.

Each type of dichromate also has a second "neutral point" which, one says, lies outside the spectrum. A slightly bluish red light which, for the normal, would be complementary to a deuteranope's "green"

neutral-point wavelength, would appear neutral to the deuteranope. A stricter red, complementary to protanopic blue-green "neutral" light, is likewise neutral as a protanope sees it. The four hues used for different R-G characters throughout the H-R-R test are those of the protanope's and deuteranope's spectral neutral points and their respective complements. Theoretically the protanope should fail to read all of the characters, of two of those hues, from end to end of the book; and the deuteranope should be unable to detect the characters of the other two hues.

The less seriously defective red-green color-blinds, the protanomalous and deuteranomalous trichromates, do not have neutral points. Saturation is not zero anywhere in their subjective spectra. The logarithms of the reciprocals of the lowest detectible colorimetric purities, plotted along the spectrum, form a curve which, everyone agrees, shows the intrinsic saturation of the observer's subjective spectrum. The color-normal's curve is high at the ends, is nowhere flat, and has a deep, steep, minimum in the yellow. The anomal's curve is depressed, sometimes only a little and sometimes more or a great deal, and has a minimum (usually its only one) in the neighborhood of the red-green dichromates' neutral points (Chapanis,[6] Wright[7]).

In the H-R-R test the earlier characters, expected to be failed by the anomals, have the hues of the dichromates' intraspectral and extraspectral neutral stimuli, hence have the hues of the corresponding anomals' saturation minima. These characters, then, should appear gray or nearly gray to the appropriate anomal—if he does see any hue in any spots, these will be so few that he cannot "integrate" the character and identify it as a triangle, circle, or cross. Here the designers admit that they made an assumption (which paid off, for they do not appear to have known of Chapanis' work). Actually, however, *any* hues at sufficiently low purities could have been made to cause the characters to blend with their gray backgrounds, but the earlier plates would not then have separated protanomals from deuteranomals, as well as separating both from normals.

The foregoing three paragraphs explain the basis on which the test makes a "qualitative" diagnosis, *i.e.*, separates protanopes and protanomals from deuteranopes and deuteranomals. In this respect the test is quite good, but in a few cases I have found it calling a "deutan" a "protan" or vice versa, and in even more cases the test recognizes the subject to be a red-green defective but refrains from particularizing him as a protan or deutan.

RED-GREEN DEFECTS; QUANTITATIVE DIAGNOSIS

The "quantitative" diagnoses offered by the H-R-R test are something else again. In their papers on the evaluation and validation of the prototype test (Hardy, Rand, and Rittler[8, 9, 10]), the designers showed plain awareness of the existence and distinctness of protanopes, deuteranopes, and anomalous trichromates—though no understanding of the nature of "extreme anomals." But in their only publication of results with the 1955 commercial "AO H-R-R" (Rand and Rittler[11]), they say such things as to lead one to suppose that they reject the psysiological and genetical classification of sex-linked color blindness entirely. In the first place, they speak of "red-green anomaly and its type" and its "degree." This is a careless use of the word *anomaly*, which has a very restricted meaning in this framework. Their "types" are not dichromasy and anomalous trichromasy, but "protan" and "deutan" categories. Their conception of "degrees" can be gathered from their statement that "we recognize that there must be gradations of defect within each of the three groups (mild, medium, strong) we have perhaps arbitrarily established."

The clear implication is that H. R. and R., or at least R. and R., believe in a continuum of defectiveness ranging from normality to dichromasy. A series of 100 or 200 plates, finely graduated in chroma, should enable one to grade the degree of defectiveness of a protan or deutan on a scale of 100 or 200—although all "protans" really comprise only one *type* of red-green color-blinds, and all "deutans" are of one other type of "anomalous" people!

This attitude seems to owe a good deal to that of the English workers, and to the picture presented by Farnsworth, particularly in the monograph by Willis and Farnsworth.[12] Here, many opinions about the classifiability of color-blinds were rounded up, both from good investigators and poor ones, and the result is horrid confusion. Furthermore, these authors and H., R. and R. have never understood how to use the Nagel anomaloscope to detect extreme anomals and distinguish them from ordinary anomals and from dichromates. Misunderstanding of the extreme anomal—almost universal in this country—is largely responsible for the common supposition that anomalous trichromasy intergrades with dichromasy. Let us get these matters straight.

The Nagel anomaloscope enables a testee to mix monochromatic red and green lights in any ratio, from zero of one to zero of the other. He sees the mixed light in a split field together with a monochromatic yellow light, whose brightness he can vary with a second control. A

color-normal can make a perfect match of color and brightness over a range of only a couple of scale units on either dial.

An ordinary deuteranomal identifies himself by setting the red-green mixture strongly greenish, to match the standard yellow. The *brightness* match he makes will satisfy the normal. The ordinary protanomal makes the mixture reddish; and the redder he wants it the dimmer the yellow he will use for his complete match, since the luminosity of the red light is low for him.

For either the deuteranope or the protanope, all three lights are interchangeable, for they appear identical in hue and are identical in saturation when at equal brightnesses. Either dichromatic defective can use just the yellow control to make a complete match with the red-green control set anywhere, but the protanope will use a dim yellow to match the pure red light, thus distinguishing himself from the deuteranope.

When the anomal has made his setting of the red-green control, its position will be separated by a number of scale units from its position as set by the color-normal. This separation is the anomal's "deviation," and is a conspicuous-seeming evidence of his abnormality. Until recent years, it was generally considered that the size of the deviation ought to express the "extent" or "degree" or "severity" of the anomal's anomaly. It became common to calculate his "anomalous quotient," a figure which expressed the size of the deviation (but nothing else), in a manner independent of the peculiarities of individual anomaloscopes which might make the average normal setting fall here or there on the red-green scale.

Another piece of information which the anomal can be made to produce is the size of his "matching range." There are several wrong ways and one right way to determine this. One may let the testee operate both controls and make five matches or ten matches or more, the controls being "thrown off" (systematically, or not) between settings. This is apparently the procedure used by Hardy, Rand and Rittler,[8, 9, 10] for in their tables they designate the matching range as a "scatter" of settings. With this procedure one is most unlikely to elicit the true matching range, since during each setting the testee is free to librate the control between non-match positions, and "feel" for the mid-point between them. Not much better is an application of the method of constant stimuli, or the practice of offering at random a series of predetermined settings to see how much of the series the testee will accept.

Only one procedure will locate the ends of the matching range and thus determine its full extent, and that is to allow the subject to use

both controls only for his first match and thereafter restrict him to the yellow one. The red-green control is moved by the examiner a little at a time, with the testee attempting to restore a complete match with the yellow control alone, first in one direction away from the original match and then in the other.

It is important to take this much trouble, for the size of the deviation and the size of the matching range have very different significances and it is the latter which indicates how little or how much trouble the particular ordinary anomal is likely to have in his dealings with color in daily life.

A large deviation is impressive to a naive color-normal who looks into the instrument after an anomal has set it, and marvels that anyone should call *those* colors alike. But, what does the deviation mean? Not that one light in the mixture is taken in excess just because it is seen dimly—the deuteranomal does not have a depression of luminosity in the green region of the spectrum, but instead has a slight gain above normal (unpublished data). Not that the light is required in excess because it is seen as having particularly low saturation—the protanomal's saturation minimum is not in the red, and the deuteranomal's is not in the green. Rather, it is because a slight distortion of even one of the componential spectral responsivity curves (characteristic of anomalous trichromasy) necessarily displaces particular hues to new, "abnormal" wavelengths. The anomal knows a sensation of, say, pure green (neither yellowish nor bluish) just as well as does the color-normal, but he and the normal do not get that sensation at just the same place in the spectrum. The anomal, at the anomaloscope, is not mixing what appear *to him* as a pure red and a pure green, to match something that appears *to him* a pure yellow. Naturally enough, he makes an "anomalous" equation.

Now the size of the matching range directly betrays the impairment of the anomal's ability to discriminate different wavelengths* as having different hues. This "poor hue-discrimination" is the feature of his vision that can get him into trouble and, if poor enough, make him unemployable in color-critical jobs. It is the direct consequence of the depression, lesser or greater, of his private spectral saturation curve. For the color-normal, saturation levels (readily altered by manipulation of stimulus purities) profoundly affect wavelength discrimination (see Tyndall[13]). What the low-saturation anomal is up against, even

*Strictly, different dominant wavelengths (of the red-green mixtures). It is all the same, for the Nagel lights are on a practically straight line on a chromaticity diagram, and the saturations of the various red-green mixtures are as high as if these were monochromatic lights.

amongst fairly strongly-colored objects, can be grasped by the color-normal if he will try naming the hue of every "gray" car that goes by. Practically no cars are truly neutral gray—all have *some* dominant wavelength, *some* colorimetric purity, which literally can only be guessed. The anomal whose anomaloscope matching range is large has to guess about objects and lights with which the normal deals entirely confidently.

The anomaloscope had not been on the market very long before its European users began to distinguish some defectives as "extreme protanomals" and "extreme deuteranomals," by reason of the extreme extent of their matching ranges. By 1928, the commonness of the extreme anomalies was so well recognized that it was proposed that each had a gene of its own, recessive to the related "ordinary" anomaly and dominant to the dichromasy (and, this has not been disproved). But in the great surveys of Waaler, von Planta, *et al*, embracing thousands of the general population, by which the incidences of the red-green defects were established, the extreme anomals were not ordinarily diagnosed and each one was counted either as just an "anomalous trichromate" or else, even more mistakenly, as a dichromate (protanope or deuteranope). The complete absence of any mention of extreme anomals, in the oft-reproduced tabulations of these classical surveys, has permitted the development of a situation in which the average color-blindness examiner is skeptical of the very existence of extreme anomaly as a distinct clinical entity.

The extreme anomal does not merely *and does not permanently* exhibit a huge matching range. When he is showing it, he may seem to interconnect the ordinary anomal and the dichromate: but this is illusory. The three kinds of defectives are qualitatively distinct, and it is essentially coincidental that their quantitative differences cause them (in respect of anomaloscopic matching range!) to *appear* to form a quantitative series with no gaps in it. Failure to understand this underlies H., R. and R.'s satisfaction with the validity of their quantitative scale and its arbitrary division into mild, medium, and strong segments.

The outstanding characteristic of the extreme anomal is a plasticity, an instability. The unrecognized occurrence of such subjects, intermingled with others in an experimental group, leads investigators to tear their hair over "the occasional cases who fail some screening tests and pass others and who often do not retest reliably."[11] It is at the anomaloscope, and nowhere else, that the extreme anomal is easily made to stand revealed for what he is.

The "extreme," making three or four free (two-control) settings,

may well cover the whole red-green scale—and be immediately set down without further ado, by the inexperienced examiner, as a dichromate. Or, an extreme protanomal's first setting may be a "deuteranomalous" one (or vice versa). It may even be essentially normal. The "extreme" may make two or more settings in succession, very close together, and be prematurely dismissed as an ordinary anomal—perhaps even complimented on his small matching range, and blithely assured that he is not really badly off, and can safely pilot a plane or what not. Extremes can only be identified when *every* anomal testee is put through the procedure outlined above, of being led by the examiner bit by bit, "by the nose," up and down the red-green scale. If this is done hastily, by too-large steps, the extreme may promptly report "no match possible" and will again be mistaken for an ordinary anomal. But when cautiously led, he will show a matching range running from one end of the scale to at least the other side of the normal's match-point (when some would call him "half-extreme") or, more often, all the way to the other end. It is this "full extreme" anomal who is most likely not to *have* to be "led"—and to be set down as a dichromate by the examiner who never bothers to look for a neutral point.

This manifestation, of a huge matching range, occurs only when the extreme anomal is in a particular state: but, he usually *is* in this state. It has been called "fatigue." The word is a most unfortunate translation from the German. The extreme anomal who is showing a "total" matching range is better called "tunable." He is not necessarily tired. His eyes certainly are not, for if he is now made to look for three minutes at a bright white area (really tiring!) his resemblance to a dichromate vanishes, and until the effect of this "neutral tuning" wears off he will have a narrow matching range and will accept as a match only such settings as would be made by an ordinary protanomal or ordinary deuteranomal, as the case may be. When he is *not* neutrally adapted, and is required to just sit and stare at a match which he has made at any distance from the "ordinary" range, the extreme anomal will report with amazement that the match "breaks up" and goes back together again—a yellow-yellow may suddenly become a green-orange field, then again an all-yellow one, as if someone had juggled the controls.

Clearly the extreme anomalous trichromate is a "dangerous" type of defective, probably as much so as the dichromate. At his best he is as abnormal as any ordinary anomal: and for periods, without his knowledge or control, he is essentially dichromatic. He cannot judge what state he is in and "make allowances" for it. In color-blindness testing

that pretends to go beyond mere normal-abnormal screening, it is essential to identify the extreme anomal and to try to make him understand his special problems.

For this, the H-R-R test cannot serve unless its category of "medium protan" quite neatly contains the extreme protanomals, and unless all extreme deuteranomals (and only they) come out of it with a "medium deutan" label. Surely the "mild" label should be expected to fall only upon ordinary anomals, and a "strong" tag would be deserved only by the dichromates.

Hardy, Rand, and Rittler[8, 9, 10] were at pains to keep from recognizing *any* extreme anomals. In their validation of the H-R-R prototype against the Nagel anomaloscope, any subject who could match over the whole red-green scale was considered a dichromate. But, "final determinations were always made with the eye unfatigued." Six half-extreme anomals were nevertheless identified—but were *excluded* from the analysis! Among their 150 defective subjects, "of the 92 subjects who were classified by the anomaloscope as anomalous trichromates, 36% were shown by the H-R-R Plates to have mild defect, 47% to have medium defect, and 17% to have strong defect." How many of these—of more importance, *which* of them—were extreme anomals, concealed by the manner in which the investigators used their anomaloscope? All of the "strongs"? Some or all of the "mediums" also?

Like the designers of all color-blindness tests produced in the past 50 years, H., R. and R., relied upon the anomaloscope as the court of last resort for the diagnosis of the defect each of their subjects *really* possessed. The H-R-R's qualitative diagnoses (of protans versus deutans) agreed with the anomaloscope's: so they had no criticism of the instrument in that connection. But the anomaloscope, as H., R. and R. used it, gave no support to their mild-medium-strong categorizations, and there they flatly dropped the pilot, saying that "settings made on the anomaloscope by anomalous trichromats do not indicate the severity of their defect." Of course they do not, when "settings" means mean-deviation values, and/or matching ranges determined with anything but their true extents. The authors' quotations from Wright[7] are not the support they think, for in his earlier use of the anomaloscope Wright paid attention only to deviations, which indeed do not correlate with anomals' hue-discrimination in the laboratory or in "practical" tests such as lanterns, color-sorting tests, and color-naming tests. Wright knows better now.[14] The relation of matching range—not deviation—to general color-discriminatory capacity was well established more than 20 years ago, but realization of this has been slow to spread (Jameson and Hurvich[15]).

When I occasionally use my own color-naming test, I have learned to predict about how many errors an ordinary anomal will make on it from the extent of his Nagel matching range, be this two scale units, or 10, or 20; but I should not dream of predicting anything from his "anomalous quotient." I have passed applicants for state and city police work who had deviations of 25 scale units and matching ranges of two units, and I have failed candidates who had deviations of five units and matching ranges of 10.

BLUE-YELLOW DEFECTS

To complete the story of what the H-R-R test purports to accomplish, a brief consideration of the "blue-yellow" defects is necessary. With only six plates devoted to them, the test may appear inadequate, in the light of its abundant provisions for diagnosing red-green defects. Actually the six plates are more than enough. Two of them are in the initial series of screening (normal-abnormal) plates. Two more have characters of much higher purity, and a testee would be called "medium" if he missed one or more but then proceeded to read correctly the last two ("strong") plates. There is no provision for a "mild tritan" or "mild tetartan" diagnosis. While, as explained above, uncritical consideration of poorly determined anomaloscopic matching ranges can persuade one that there are continua from the mildest protanomaly and the mildest deuteranomaly to protanopia and deuteranopia, there is not even such a reason for anyone to think that there is a quantitative continuum of either "tritan" or "tetartan" defects, leading from "strong" down to normality.

Hardy, Rand and Rittler themselves coined the term "tetartan," which by analogy with the definitions of Farnsworth's protan, deutan, and tritan implies the existence of tetartanopia and also a "tetartanomalous trichromasy." The latter hypothetical defect is not known to exist. Tetartanopia is real enough, although not a dozen cases have ever been described. The tetartanope has two neutral points within the spectrum. Their wavelengths (for one case) are the dominant wavelengths given to the H-R-R tetartan characters—one character on each of the six B-Y plates. What sort of defective the designers thought might ever come out "medium tetartan," they have never said. Nor have they justified requiring every purchaser to pay for the six tetartan characters in the first place—there is not at present a single "tetartan" known to be living in the entire Western Hemisphere. The only one *ever* reported died near Seattle six years ago.

What a "medium tritan" might be is not clear either. Tritanopes, whose defect is certainly a strong one, are not as rare as they were

thought to be until just a few years ago. There may be as many as five in every 65,000 people (of either sex). True tritanomaly (sex-linked) is extremely rare—most supposed tritanomaly is probably a mild forme fruste of tritanopia. The tritanope's spectrum contains two hues, and a neutral point a little greenward from the locus of pure yellow. A strongly bluish purple, practically violet, is complementary to this, and the corresponding hues are those of the H-R-R's six "tritan" characters. The designers have never reported the performance, on either the prototype or the commercial test, of a single tritanope, tritanomal, or tetartanope. Three tritanopes, and two tritanomals (respective sons of color-normal sisters), to whom I have given it, all made "strong tritan" scores.* None missed any of the "tetartan" characters; but whether a tetartanope would miss them, and not miss also the tritan characters, remains to be seen.

In my opinion, the six B-Y plates might better never have been developed at all. Their place could well be taken, in a future edition, by a single "tritan" plate modeled upon such a one as has been published by Farnsworth[16] (and see Wright[14]). Whether this distinguished the genuine tritanomal from the tritanope or lumped them would not matter —in any event, *any* blue-yellow defective uncovered by any clinical or industrial color-vision examiner should be passed on to the nearest color-blindness researcher for complete study, and not buried in the files of an employment office.

SOME RESULTS

When I first began using the AO H-R-R test, it was with great curiosity to see how neatly its quantitative "medium" labels might fit the bothersome categories of extreme protanomaly and extreme deuteranomaly. I was not discouraged by the fact that in their pilot studies[8, 9, 10] the designers found many "mediums" but recognized no "extremes," for their methods could hardly have been better designed to conceal the "extremes" in their defective group.

At first, "mediums" seemed to be accumulating rapidly, and I decided that when I had found fifty I would call a halt and publish a tabulation of their diagnoses in terms of the accepted "ordinary anomal —extreme anomal—dichromate" classifications. Assuming however that only ordinary anomals should come out mild and only dichromates should come out strong, I found so many subjects misclassified by the H-R-R that my goal changed to a total of about fifty mediums-plus-other-misdiagnoses.

*In the only other pseudoisochromatic-chart test that contains "blue-yellow" plates (the Stilling test, in its later editions), these were designed by Engelking around three tritanomals available to him. The plates are reputed *not* to catch tritanopes.

TABLE 1

Consecutive cases (previously informed that they were "color blind"), as diagnosed by the AO H-R-R test:

| | Normal | Mild Deutan | Medium Deutan | Strong Deutan | Mild Protan | Medium Protan | Strong Protan | R-G defect, unclassified as to type: Mild | Medium | Strong |
|---|---|---|---|---|---|---|---|---|---|---|
| Normality | 21 | — | — | — | — | — | — | — | — | — |
| Ordinary Deuteranomaly | 2 | 6 | 7 | 2 | — | — | — | 2 | — | — |
| Extreme Deuteranomaly | — | — | 7 | 4 | — | 3 | — | — | 1 | 1 |
| Deuteranopia | — | — | 1 | 7 | — | — | 1 | — | — | — |
| Ordinary Protanomaly | 1 | 1 | — | — | 1 | 1 | 1 | 2 | — | — |
| Extreme Protanomaly | — | — | — | — | — | 7 | 1 | — | — | — |
| Protanopia | — | — | — | — | — | 6 | 4 | — | — | — |
| Undiagnosable | — | — | — | 1 | — | — | — | — | — | — |

As diagnosed with other tests, principally the Nagel Anomaloscope:

The accompanying table, however, contains all subjects accumulated over a particular period of time, who were given the H-R-R test and otherwise had just one thing in common: every subject had already been told by someone else, at some time, on the basis of some test (other than the H-R-R) that he or she was "color blind," and had come to me for an adequate analysis and accurate diagnosis. Among these consecutive subjects, 70 really were defectives, 21 not.

I always gave the H-R-R test myself, with the subject seated on a stool and looking horizontally. The plates were presented in a vertical position, the examiner standing and holding the book against his chest and thirty inches from the subject's eyes: the subject was allowed to see each plate for three seconds (but with no limitation on the time allowed to make his report). The illuminant was the approved Macbeth lamp, not however on its easel stand (which I consider a nuisance), but mounted to shine on the plates at 45° incidence from the subject's right. The illuminance on the plates was 40 footcandles.

I also personally administered all other tests, which were those of the Walls-Mathews battery[17] as used by Walls and Heath,[5] with the Nagel as the only anomaloscope. For dichromates, the presence of a protanopic or deuteranopic neutral point was confirmed, by the method of Walls and Heath. Differential diagnosis depended, of course, chiefly upon the anomaloscope: but for the occasional "odd-ball" case (the kind for which the researcher patiently waits!), the other tests were indispensable supplements.

It needs to be emphasized that the cases tabulated are not comparable with an equal number of defective individuals taken at random from the general population. The few normals included had previously been diagnosed as color blind: most were appellant applicants for the California Highway Patrol, who had "failed" the inadequate color-vision test incorporated in the Bausch and Lomb Ortho-Rater.

Among the 70 defectives, few were "mild," and a majority were "medium"—the percentages being 17.1% mild, 47.1% medium, and 31.4% strong. When Hardy, Rand and Rittler[8, 9, 10] had tested 150 run-of-the-mine defectives with the Prototype H-R-R their incidences, which they thought would hold for any larger number, were 22.7% mild, 30.7% medium, and 46.7% strong. Rand and Rittler[11] obtained somewhat different values, however, when they gave the H-R-R prototype to 97 defectives (two-thirds of them, "new" [?] cases): 29.9% mild, 29.9% medium, and 40.2% strong. These same 97 are the longest string for which AO H-R-R performances have been given. Among them, Rand and Rittler found 28.1% mild, 34.4% medium, and 37.5% strong with the commercial test.

The discrepancy between these figures and my own is, I think, almost entirely due to the selective factor operating in my group—previous diagnosis as "color blind." Most ordinary anomals do not suspect that their color vision is abnormal unless and until they are given a test and told that it is. Many more ordinary anomals would have been in my group, and shown up as "mild protans" and "mild deutans," if I had found my subjects by testing everyone in a captive general population, such as the student body of a school.

In my hands, the AO H-R-R test called no normals "defective" but it did call "normal" two ordinary deuteranomals and one ordinary protanomal. One of the deuteranomals had a Nagel deviation of 20 scale units and showed the usual contrast effect against the pure red, but his matching range was only *one* unit long and he was nearly perfect in color naming; he is now a valued police officer. The other had a deviation of 15 units, a matching range of only six. The protanomal had a normal luminosity curve and reported some reddishness in his RDP, and he had a Nagel deviation of only seven units but a matching range of 11 (he could not accept the *average* normal setting). His color-naming was almost perfect, and he was gingerly passed for the Highway Patrol.

The least abnormal rating given by the H-R-R is "mild red-green defect, unclassified as to type." Here the subject has erred on the initial "screening" plates (in two showings), but not on the "diagnostic" Plates 7-20, and cannot be diagnosed even qualitatively, as either "protan" or "deutan." I had four such cases in my series, two of them actually ordinary deuteranomals and the other two, ordinary protanomals. One of the former was deuteranomalous by all tests, with a Nagel deviation of 12 units and a contrast effect, and with a matching range of seven units. When tested he was a municipal police officer. His matching range and especially his poor color-naming performance caused rejection for the Highway Patrol. The other reported an RDP, with reddishness in it, had a Nagel deviation of 23 units and a matching range of only four, no contrast effect, and misnamed no colored chips; he was passed for the Highway Patrol. One of the protanomals was typical as regards luminosity curve and blue RDP, had a Nagel deviation of 20 units and a contrast effect against the green, but a matching range of only two units; surprisingly, his color naming was poor. The other was also protanomalous by all criteria and had a Nagel deviation of 20 units with a matching range of six.

The cases dealt with thus far do not represent serious misdiagnoses. Probably none of the three "H-R-R normals" would be a risk in most

color-critical vocations. Most examiners would probably pass all four of the "mild unclassifiables" for occupations which profess to demand normal color vision, although I passed only one of them.

The only "mild protan" in my series was indeed an ordinary protanomal, and it was satisfying to find that six out of the seven "mild deutans" were only ordinary deuteranomals. The "mild deutan" who turned out to be an ordinary protanomal—a qualitative misdiagnosis—requires special explanation. There is no doubt of her clinical protanomaly, "by definition," since her Nagel deviation of four units is redward. She is however an "odd-ball." Her RDP is not blue but "red with an orange cast" (a unique report!), and while her relative luminosities are barely protanomalous, her requiring of an elevated voltage on the red lamp may only mean that she is seeing the standard green lamp abnormally bright: at the Nagel, she cannot get the yellow light bright enough to match the pure green (a rare phenomenon). She is a successful medical laboratory technician: but on my color-naming test, while she seriously misnamed none of the 20 chromatic chips, she called green or greenish four of the nine grays (Munsell neutrals, whole numbers apart in value), and called two others bluish gray. She called the pure green of the Nagel bluish green, when it was against a yellow as bright as it could be made. Although her father (unavailable for testing) is reputedly somehow color blind, there seems a good chance that she is only heterozygous for some gene, and has an irregular defect.

Of the 14 subjects who came out "strong deutan" there are two—the ordinary deuteranomals—who represent intolerable errors on the part of the H-R-R. None of the battery data for either of these men sets him off in any way from the mass of deuteranomals. Their Nagel deviations are 20 and 33 units, and with the greater matching range for the two only 10 units, neither is under the least suspicion of being an "extreme," let alone a deuteranope. The strong deutan label on my one "undiagnosable" subject is more excusable. He has one pure deuteranope brother and three color-normal brothers and a color-normal mother, so that his only defect-gene is one for deuteranopia. His RDP reports are deuteranoid, his luminosity curve barely protanomalous. At the anomaloscope he is perfectly deuteranopic and perfectly stable, with no responsitivity to neutral adaptation (*i.e.*, none of the behavior of an extreme anomal). But he can make a neutral-point equation only when the field is reduced from 4° to 2°, and even then he cannot get rid of some "pinkishness" in the *gray* field-half. The "neutral point" he does then manifest is a *protanopic* one ($\lambda$490.7m$\mu$: 7500° K).

I call him undiagnosable (although I am sure of his deuteranopic genotype), for the purposes of this paper, to put myself in the position of a clinical examiner who would not know about the subject's critical relatives, could not interpret the genetical situation if he did, and would suppose him to be just like his deuteranopic brother.

The "strong protan" label fell properly enough upon four protanopes, but quite improperly upon one ordinary protanomal who is perfectly orthodox in all respects, and even mild by the criterion of Nagel matching range (four units: deviation, 23). His H-R-R errors through the "medium" plates (12-14) were consistently "protan": his performance was deutan on Plate 15, protan again on 16. I can nowise account for his bad showing on the H-R-R.

The "strong protan" determination of one deuteranope seems a serious misclassification. The only thing protanoid about this young man is his luminosity curve, which is that of an average protanomal. Everything else about him is deuteranopic. He sees no RDP under any circumstances. He is deuteranopic at the Nagel and makes a sharp and stable neutral-point setting. His neutral point wavelength (492.2 $m\mu$: 7500° K) is very low. I have only one other deuteranope who lies lower, separated by a gap from my highest-wavelength protanope (see Walls and Heath[5]). Actually, this subject's H-R-R performance was barely "protan" rather than "strong R-G, unclassifiable": for, he saw *no* characters on Plates 8, 9, 11, 12, 13, 14, and 16, and made the protan errors only on Plates 10 and 15. This performance may be somehow related to the unknown basis of his luminosity curve (has he genes for both deuteranopia and protanomaly?).

Extreme anomalous trichromasy and "medium extent of defect" conspicuously fail to coincide. A "medium deutan" is as likely to be an ordinary deuteranomal as an extreme, and an extreme deuteranomal has only a two-to-one likelihood of coming out "medium" rather than "strong." Hardy, Rand, and Rittler, ignoring their own instruction to consider a testee "medium" if he makes *any errors* on the three "medium" plates, said that "the subject who fails only one plate of this series is probably more nearly borderline between mild and medium in extent of defect than is the subject who fails all three plates.[8, 9, 10] This seems to push the mild-medium border inside of medium territory. Among my ordinary deuteranomals who tested medium deutan, one did misread only one of the "medium" plates, and one misread two plates, but five misread all three. One "medium" extreme deuteranomal misread one "medium" plate and thus almost earned a highly inappropriate "mild" label: but three extremes missed on two "medium" plates and three

others misread all three. The one deuteranope who was "medium" instead of "strong" missed only two of the medium plates. This man, an interstate trucker, is able to hold his job in spite of I.C.C. regulations because he can always pass yarn and lantern tests. Passing these "practical" tests hardly makes him safe, however—repeatedly, he has driven through a flashing red signal light which he thought to be amber. He is a full-blown deuteranope, with a neutral point at $\lambda 496.2 m\mu$ (7500° K).

The "medium protan" category does not even come as close to restriction to anomals as the "medium deutan." It contains almost as many protanopes as protanomals. The one ordinary protanomal called "medium" failed only one of the three medium plates, all six of the "medium" protanopes misread all three, and of the "medium" extreme protanomals three failed one plate, two failed two plates, and two failed three. To this extent, there *is* a gradient of protanoid defectiveness *within* the "medium" category. This seeming support of the ideas of H., R., and R. is shattered however by the fact that three "medium protans" were actually extreme *deuter*anomals. True, any one of these might have come out "deutan" if retested: but, in ordinary use the H-R-R test would not be given twice to the same subject—at least, not by the same examiner in the same sitting. Moreover, H., R., and R. have emphasized that when retest results do not agree with initial results, the *first* label assigned to the testee is more likely his correct one.

For each of the three extreme deuteranomals who tested protan, there is perhaps a special reason for this. In one case, the luminosity data were not protanoid and for one eye there was no RDP, but for the other eye there was a possibly protanoid one. The entire anomaloscope scale could be matched, but the normal's setting "broke up" repeatedly. When two "free" matches were made, the first was protanomalous and the second deuteranomalous: this second match was rejected following neutral adaptation. In the second case, luminosities were deuteranoid, but instead of no RDP a "blue-purple" one was seen. Anomaloscope behavior was perfectly "extreme deuteranomalous": the subject made two free matches which were both deuteranomalous and 22 units apart, matched the pure green (but not the pure red), accepted the normal's match, repeated the match against pure green but found after neutral adaptation that it appeared "yellow-green versus orange," and then (while still neutrally adapted) readily accepted an ordinary deuteranomal's values, set in by the examiner. This subject was the only red-green defective in the series who made any "blue-yellow" errors—on Screening Plate 5 (1955 edition) he read only the circle: on Plate 6,

only the triangle. The third man could match from the green end to beyond the normal's setting (but when the normal match was "broken up" it was reported as *green* versus orange!) He saw no RDP under any circumstances. But his luminosity for red light was protanomalous.

One extreme deuteranomal had to be called "medium R-G, unclassified," inasmuch as he made exactly as many protan errors as deutan (including errors on all three "medium" plates). His extreme deuteranomaly was entirely typical, with no extraneous features whatever. This was also true of the extreme deuteranomal rated "strong R-G, unclassified." His only diagnostic error was to read only the circle on Plate 11—he missed *all other* R-G characters up to and including Plate 15 (and then read Plate 16 correctly).

In the present series of cases, all but one of the deuteranopes takes a "strong" label, and of the "medium" deuteranomals half are extremes and a large majority of the "ordinaries" misread all the medium plates. It would seem that the H-R-R's mild-medium boundary lies within the group of ordinary deuteranomals, separating those whose color aptitude is fair from those in whom it is bad. The medium-strong boundary lies within the group of extreme deuteranomals, and nearly all deuteranopes are "strong" enough to keep out of the medium class. This is probably about as close a relationship between the H-R-R's quantitative classification and the true physiological-genetical typing of deuteranoids as could have been expected.

With the protanoids the situation does not look even this good. Here the mild-medium boundary *may* coincide pretty well with the ordinary-extreme "boundary" (more ordinary protanomals would be needed, to tell). But the medium-strong boundary appears to lie nearly half-way through the protanope group—the "mediums" include about all of the extreme protanomals and about half of the protanopes. Yet, it is inconceivable that "defectiveness" should vary from protanope to protanope in any such way that protanopes could be arranged in a linear series ranging from a least defective to a most defective one! On what basis, then, can the H-R-R test be distinguishing "medium" protanopes from "strong" protanopes?

A first hunch would be that the separation is on the basis of neutral-point location. Suppose the chromaticities of the protan character-spots on the two "strong R-G" H-R-R plates are suited to the wavelength (and complement) of the average neutral point of the ten protanopes in the present series. Those whose neutral points were at wavelengths much longer than average might then see the circle and triangle on Plates 15 and 16 about as well as they saw the cross and circle. These particular protanopes would have to be scored as "medium."

This does not seem to be the explanation. I now have 7500° K data for 24 protanopes; they range from λ488.7mμ to 492.0, with the mean at 490.4 (s.d. 0.89). The neutral-point wavelengths of the six protanopes found "medium" here are 489.4, 490.0, 490.7, 491.0, 491.1, and 491.7 mμ. Those of the four "strong" protanopes are 489.5, 490.0, 490.5, and 490.9 mμ.

Another possibility is that the dominant wavelengths of the characters a strong protan should not see have been adjusted to an "average protanopic neutral-point wavelength" which is rather too short. This would promote, not reduce, the legibility of those characters for a deuteranope: and, a proportion of protanopes would be able to read them and thus escape the "strong" classification. If on the other hand the hue of the blue-green characters lay at too long a wavelength, some deuteranopes could not read them and would check out as "strong R-G, unclassified."

The puzzle of the "medium" protanopes cannot be cleared up without information as regards what the dominant wavelengths of the "strong" characters actually are. I have not been able to get this information. The American Optical Company cannot say what the values are, or even what they are supposed to be. The values designed into the Prototype H-R-R were based upon the neutral points of 18 protanopes and 18 deuteranopes,[18] determined[19] by the method of Walls and Mathews.[17] There seems to be no one who can or will say what those figures were. (Rand has repeatedly avoided direct requests for them. Hardy died a year before the first edition of the AO H-R-R was published. Rittler's status has been that of a technician.)

EVALUATION

Findings with the H-R-R test require to be summarized with respect to each of the three purposes the test is supposed to serve.

Firstly, how well does the test detect color blindness—how perfectly does it separate all normals from all abnormals? With regard to "blue-yellow" defectives, no one can say. It will certainly trap tritanopes and tritanomalous trichromates, but it has never been tried on known cases of the mysterious "mild blue-yellow defects" which are reported from time to time (usually associated with other conditions). As a normal-abnormal screen in the present series of cases, it called no normals defective but it did call three defectives, out of 70, normal. The commercial form of the test has been compared with other chart tests by Sloan and Habel[20] and by Belcher, Greenshields, and Wright[21] (who used daylight), and ranked inferior to the Ishihara and Dvorine tests in both studies, in the first because it called defective two normals out of 100 and passed four defectives out of 44, in the second because it passed two

defectives out of 38. As a normal-abnormal screening device, the AO H-R-R is perhaps as good as the Ishihara, the Dvorine, and the test which it displaced from the AO catalogue.* It is certainly not any better than any of these, and it costs more than would any of them, combined with a single good tritanoid plate such as Farnsworth's.[16] In the present study, the anomaloscope caught the three defectives the H-R-R test missed.

Secondly, how well does the test make its qualitative diagnoses—how accurately does it identify red-green defectives as protanoid or deuteranoid, and blue-yellow ones as "tritan" or "tetartan"? For the test even to attempt the latter distinction is presumptuous. Tetartanopia is itself a tritanoid defect, and genotypically it is probably tritanopia. At any one time there are only a couple of known living tetartanopes anywhere in the world. For a chart test to be marketed, with provision for differentially diagnosing tetartanopes, makes little sense.

The designers of the test have not shown how accurately the commercial version identifies protanoids and deuteranoids. Rand and Rittler[11] have only compared the diagnoses made by the AO H-R-R and the Prototype H-R-R on 97 defectives, only a third of whom were ever checked on the anomaloscope. In Sloan and Habel's study,[20] no subject was reported to have been found "protan" on the AO H-R-R and "deutan" on the Nagel, or vice versa. Wright[14] discussed the diagnostic abilities of the AO H-R-R and the Nagel, and included the latter in a suggested minimal test-battery, but expressly refrained from singling out any chart test as superior. Belcher, Greenshields, and Wright[21] checked the diagnoses of 38 defectives, made by five chart tests, with the anomaloscope. If the AO H-R-R misdiagnosed any subject qualitatively, they do not mention the fact.

In the present study, the AO H-R-R made a serious number of misdiagnoses. It called a deuteranope and three extreme deuteranomals "protan," called one ordinary protanomal "deutan," and called "deutan" one subject who, while he was purely deuteranopic according to the Nagel, was made to seem ambiguous by his barely protanoid luminosity curve and questionable neutral point. I consider as qualitative misdiagnosis also, the H-R-R's inability to classify four mild, one medium, and one strong red-green defectives, none of whom was in the least ambiguous at the Nagel. With 12 out of 67—18%—of its "qualitative" red-green diagnoses thus incorrect, I cannot consider that the AO

*I.e., the Revised Selection. It was this test, *not* the AO H-R-R, which came out the poorest of four chart tests compared—as normal-abnormal screens—by Kettesy.[22] An erroneous report of Kettesy's work in the 1956 *Archives of Ophthalmology* (volume 55—see page 898) makes the AO H-R-R out to be even poorer than it really is.

H-R-R lives up to its claims in this respect.

A researcher on color blindness, or its genetics, who depended on the AO H-R-R could be badly misled. The test may put the wrong label on an orthodox defective. It is sure to put one of its orthodox labels on any unorthodox subject, and the investigator will not take the special interest in that subject that he should. The test can even suggest that a subject *is* unorthodox—but in a way quite different from that in which the testee actually is peculiar. I have had a fantastic demonstration of this, in a case outside the scope of the present investigation. This is "A.H.C.," whose vision is color-normal by way of her right eye, but dichromatic and with a deuteranopic neutral point by way of her left. Her "deuteranopia" is unorthodox but is certainly not combined with any tritanoid defect.[23] However, the AO H-R-R test says that her left eye has a "strong deutan defect" *and* a "medium blue-yellow defect, unclassified as to type."

Even if the test identified correctly every protanoid and every deuteranoid (including the ones it calls "normal"), this kind of information would be entirely useless *unless* its "quantitative" diagnoses were completely reliable and meaningful. It does no good to anyone, for an examiner to be able to tell a testee: "Not only am I sure that you are color blind, but I am sure that you are a protanoid and not a deuteranoid —however, I cannot tell whether you are a protanope or a protanomal." A test which enabled only this would be no more valuable than one that pretended to be nothing but a normal-abnormal screen. The examiner would be better advised to buy a Dvorine test and a small daylight fluorescent luminaire, than to spend the sum required to use the AO H-R-R.

Thirdly and lastly then, how reliable and how meaningful *are* the AO H-R-R's "quantitative" diagnoses? It has never been claimed that the test would divide dichromates from anomalous trichromates, let alone that it would separate the latter into extremes and ordinaries —*that* distinction, the designers did not make even in their pilot studies, although they had the means. Even so, they had apparently hoped that the test would make these divisions: for, in explaining why 13 out of 86 anomals were graded "strong" defectives by the Prototype H-R-R, Rand[24] said: "As to the 'why' of this, we can only conclude that we were unable to obtain a sufficiently high chroma in stable surface colors to make the differentiation between anomalous trichromats and dichromats." Finding only one of her dichromates earning a "medium" rather than a "strong" tag, she "thought it likely that the percentage of such cases is small,"[24] and clearly hoped that the "strong" label could be

assumed to mean dichromasy (but, seven of the 19 dichromates in *my* series are "mediums," a large percentage).

I have made it clear, above, that I have confidence only in the kind of "quantitative" classification an anomaloscope can give, as a basis for prediction of the safeness or dangerousness of color-blinds as personnel in color-critical jobs and professions. On the basis of the present study, the most that can be said for the AO H-R-R is that if it says a defective is "mild," he *is* mildly defective, for he is an ordinary deuteranomal or protanomal. On the other hand either an ordinary deuteranomal or an ordinary protanomal may be labeled mild, medium, or strong by the H-R-R—and either the medium or the strong label may be taken on by a dichromate, an extreme anomal, or an ordinary anomal. Rand now admits that "just how valuable for practical purposes is the differentiation between medium and strong defect, we are not sure."[24] But to lump the "medium" and "strong" plates and give a future edition of the test only "mild" and "serious" labels to confer, would only tar most ordinary anomals with a "serious" brush and frustrate any examiner who might want to try to salvage some of them if only he could recognize them.

For anyone who does not want anything more than a normal-abnormal screen, or is satisfied with the predictive value of a lantern test (which tests vocabulary as much as physiology), the H-R-R is acceptable. But for conscientious work in the advising of employers and the vocational guidance of youth, there is still no substitute for an anomaloscope. This does not, however, have to be a $1,000.00 Nagel. For a cost somewhere between that of equipment for Dvorine testing and equipment for H-R-R testing, one can build or have built an anomaloscope—one so simple that it contains no "optics" at all, and yet is capable of really doing everything that the AO H-R-R claims to do (see Walls[25]).

*Note added in proof*—Since the above was written, R. G. Fry has published a study in which the performances of 144 color normals and 144 red-green defectives were compared plate by plate on the AO H-R-R and five other pseudoisochromatic-chart tests (*v. Graefes Arch. für Ophth.*, 160: 301-320: 1958). Two of these other tests mislabeled fewer normals as defective. The Rabkin test was best of all for qualitative diagnosis of protanoids and deuteranoids. None of the tests made "quantitative" diagnoses which fitted the anomal-dichromate classifications afforded by the anomaloscope.

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# OBSERVATIONS ON THE FITTING OF CORNEAL CONTACT LENSES*

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For the purpose of this article the term "Corneal Lenses" is intended to include all contact lenses fitted within the limits of the cornea, i.e., Tuohy type corneals, micro-corneals, micro-rim and contour lenses.

As far as we know corneal lenses were originally used by Dallos for refraction purposes only and the first popular type to be generally fitted was the full size corneal lens developed by Tuohy[1] in 1948. This lens was a double curve lens having an overall diameter of 11.50 mm. with a 1 mm. bevel and was worn with varying success. At the last International Optical Congress held in London in 1951, J. C. Neill of Philadelphia considered that these lenses were worn successfully by only 25 per cent of the patients fitted.

Subsequently Neill[2] and Dickinson,[3] in collaboration with Soehnges of Munich developed the micro-corneal lens, originally a single curve lens having a diameter of 9.5 mm. and a center thickness of approximately 0.25 mm. The lens had no definite bevel and its production to a very high standard was achieved in England by G. Nissel. This lens had two principal advantages over the full size lens: the margin was well within the limbal area and by virtue of its size a marked reduction in center thickness and weight was possible. Theoretically such a lens should reduce limbal and lid irritation and float more easily than the heavier Tuohy type lens. This development was a real step towards the perfection of the corneal lens and wearing time improved in many cases. It may be true to say that the introduction of micro-lenses advanced the fitting of corneal lenses to such a degree that this technique, which previously had been regarded in a very conservative manner, gained a popularity equal to that of the conventional haptic lens.

As optometrists gained experience, it became obvious that a single curve lens was not ideal in the majority of cases: anatomically it was incorrect. The flattening of the peripheral zone of the cornea created many problems, and so a flange of flatter radius was introduced and

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the micro-rim lens was born. The width of the flange and the degree of flattening varied with the experience of the fitter and the contour of the individual cornea. This lens was a further step forward and is, indeed, used very extensively today. A natural concomitant of the introduction and success of the flange was the more detailed consideration given to the corneal contour and the area embraced by the central optical zone. As a result of his observations Bier[4] considered this zone to be limited to an area of approximately 6.00 mm. and introduced the "Contour" lens which is, in fact, a modification of the micro-rim lens having a similar overall diameter but with a wider flange reducing the primary optical zone to 6.5 mm. By this limitation of the optical zone it is possible for the central curvature of the lens to approach that of the optical zone of the cornea. The lens should center better and avoid excessive sag or slide with their attendant problems. Nevertheless it would be unwise to regard the contour lens as the panacea of all ills and, it must be remembered, each of the foregoing types have been worn with success.

(1) *Full Size Corneal Lenses.* It has been stated that the original corneal lens could be worn with success by 25 per cent of the patients fitted. Experience has shown that these were patients with corneas of large diameter and, very often, large palpebral apertures. Failure occurred when the flange of the lens created limbal pressure especially in the upper limbal area. This pressure is accentuated by a narrow palpebral aperture and especially by tight upper lids. The appreciation of this problem led to the production of the micro-corneal lens.

(2) *Micro-Corneal Lenses.* By reducing the overall diameter of the corneal lens, and consequently its thickness, limbal irritation was reduced and it became possible to fit corneal lenses to many patients who were unable to tolerate full size lenses. Nevertheless, problems still remained. The single curve micro-lens forced optometrists to adopt an inner radius markedly flatter than the optical zone of the cornea in order to avoid limbal pressure on versionary movements. This, in turn, created other problems. In certain eyes such a lens would tend to ride eccentrically upon the cornea: when this occurred in the horizontal meridian the lens seemed to "bottom" on the flatter sclera in the para-limbal region much in the way a flat bottomed dinghy settles firmly on the slope of a beach. K. C. Hall has referred most frankly to this problem in his paper to the 4th International Congress of Contact Lens Specialists.[5] It became obvious that the single curve micro-lens, while a marked step forward in design, was not the final answer to the problem and was unsuited to certain types of corneas, especially in high degrees

of astigmatism. Anatomically it was incorrect and a double curve micro-lens was introduced.

(3) *Micro-Rim Corneals.* The diameter of the flange (or second curve) and the degree of flattening over the primary curve varied from patient to patient and with the experience of the fitter. At first some optometrists adopted a flange of only 0.50 mm. in width and with a radius at times as much as 2.00 mm. flatter than the major curve. The principle, however, was established that a double curve lens was anatomically correct and such a lens enabled a closer alignment with the cornea while avoiding pressure. Further consideration of the structure of the cornea and of the regular central zone led practitioners to increase the diameter of the flange thereby reducing the diameter of the central or optical zone. Bier referred to this modification of the double curve micro-lens in his paper given to the Second National Contact Lens Congress.[6] This lens more closely follows that of the flattest curvature of the central corneal zone. The contour lens, as it has become known, normally has a diameter of 9.5 mm. and an optic of 6.5 mm. The degree of flattening applied to the flange must vary in individual cases but in general a minimum of 0.50 mm. will be found necessary in those patients where both corneal and scleral radii are steep increasing to approximately 0.80 mm. flatter for those patients whose central radius may be considered maximal.

(4) *The Contour Lens.* The contour lens has shown several advantages in practice over its predecessors, namely: (a) The bearing surface on the cornea is extended so that both weight and pressure are more evenly distributed thereby reducing the likelihood of epithelial disturbance. (b) The vertical lag so often encountered in high plus corrections is considerably reduced. (c) The centration of the lens upon the cornea is improved and the problem of lateral slide and limbal irritation is largely overcome. (d) By virtue of the reduced optic, patients with high astigmatism can be satisfactorily fitted. In these cases the writer finds the most satisfactory fitting is obtained if the optic radius equals that of the flatter corneal meridian. I do not agree with the method advocated by Bier[6] that the radius chosen should be steeper than the flatter meridian, which must create apical clearance, as this very considerably reduces the bearing surface of the lens and induces lag which can only be compensated by the creation of a physical brake at the margin of the optical zone.

CORNEAL STAINING

Much has been said and written concerning the danger of corneal abrasions by the wearing of corneal lenses and this is obviously a matter

of importance. Widely divergent views seem to be held on the occurrence and frequency of corneal staining as evidenced by wearers of corneal lenses. Some practitioners state that they rarely encounter this phenomenon except during fitting sessions. My own experience is that staining does occur fairly frequently and for a variety of reasons. While staining itself is not a cause for alarm it is important that it should be observed and the cause determined and eliminated. The commonest types of staining and their causes are enumerated:

1. *Central or Apical Staining.* The stain is fairly regular in shape and density perhaps fading at its margin, and covers an area of approximately 3-4 mm. This form of staining is invariably due to an incorrect curvature of the inner optic. It commonly occurs as one of a group of "tight" symptoms in which case the lens will be found to cling too firmly to the corneal surface. Conversely I have found corneal staining to occur if a lens is too loose and by excessive movement chafes the apex of the cornea. This form of stain will disappear on correction of the optical radius and/or type of lens employed.

2. *Para-Central Staining.* Small, punctate or flecked stains can often be seen adjacent to the central or bearing surface of the cornea. These are nearly always caused by dust or mucous particles carried in and lodged by the tear fluid. Patients should always be urged to remove their lenses and thoroughly cleanse them if they suspect any foreign body may have entered the eye and become lodged behind the lens.

3. *Striated Staining.* Occasionally arcuate striated staining is seen during the initial stages of wear by patients who are nervous and experience difficulty in inserting their lenses. An incorrect and clumsy insertion will cause the edge of the lens to disturb the corneal epithelium creating an arcuate stain. A similar, but more irregular, striated stain is occasioned by fine strings of mucous which can creep beneath the lens surface. In such cases attention must be given to excessive mucous formation, the bathing of the eyes before insertion with an astringent lotion will help, and if nasal catarrh is responsible the patient should be referred for medical treatment.

4. *Peripheral Staining.* A broad arcuate stain may be seen either immediately within or without the limbal region, frequently in the upper half of the cornea. This is due to pressure in the limbal region exerted by the flange or periphery of the lens and arise from a variety of errors in fitting. The lens may be too large and the flange too steep: the lens may be of correct size but too loose and is "riding high" (in such a case the lens tends to "bottom" on the upper sclera and pressure will be created in the upper limbal area). Some patients, surprisingly will

tolerate this condition but others experience irritation after a relatively short wearing time. This form of staining is rarely seen with a tontour lens and, in any case, is not encountered if the lens is fitting correctly.

VISUAL DISTURBANCES

Frequently patients have complained of visual disturbances with corneal lenses and these can be divided into two main categories:

(a) *Spectacle Blur.* This phenomenon is usually experienced after prolonged use of lenses having an inner radius considerably flatter than the optical zone of the cornea. Such a lens appears to create a temporary flattening of the corneal apex and a corresponding reduction in the degree of myopia (in the case of a hypermetrope the error is, of course, increased). On removal of the lenses the patient experiences blur with his spectacle correction which is particularly marked in near vision. The corneal condition returns to normal fairly quickly in most cases and the phenomenon does not occur if the inner radius of the corneal lens is steepened to approximate the keratometer reading.

(b) *Marginal Confusion.* This occurs in a double curve lens either through excessive displacement of the lens on versionary movements of the eyes (in a patient with high plus lenses this may occur due to vertical lag in the primary position) or through too narrow an optic being employed for patients whose pupillary diameter is excessively large. In the first instance correction can be made by steepening the inner optic radius and, if necessary, by decentering the optic if confusion occurs in one direction only. In the second instance it is desirable to fit an oversize lens providing a larger optic while maintaining an adequate flange.

PALPEBRAL APERTURE

Excluding pathologic cases, patients having a large palpebral aperture will be found to have correspondingly large corneas. In such cases a standard size lens is unsatisfactory cosmetically and functionally. It will rest within the palpebral aperture inducing displacement by the upper lid with consequent visual disturbances. Both the appearance and comfort of the patient is improved by fitting an oversize lens.

SUMMATION

1. While all types of corneal lenses can be worn with success by certain patients it is desirable that a corneal lens should follow the contour of the cornea as closely as possible and most of the problems associated with corneal lenses are eliminated by the employment of a contour lens where the two basic curves are carefully blended and the size of the optic approximates the regular central zone of the cornea.

2. While an overall diameter of 9.5 mm. with a 6.5 mm. optic

is generally employed it is necessary for certain patients to increase the diameter of both the lens and the optic.

3. While corneal staining may be observed in many patients, especially in the early stages of wear, this is not, of itself, a cause for alarm but the patient should be kept under observation until the cause has been determined and eliminated.

4. The various types of visual disturbances which occur arise from an incorrectly fitting lens and, in general, are brought about by the employment of either too flat a radius of the inner optic or too narrow a chord.

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## ANNOUNCEMENT

### LOS ANGELES COLLEGE POST-GRADUATE SUMMER SESSION

The Los Angeles College of Optometry will hold its 13th annual Post-Graduate Summer Session June 1 through June 19. Courses to be given will include, *The Clinical Examination and Treatment of Strabismus*, Dr. Merton Flom: *Fundamentals of Contact Lens Practice*, Dr. Max Schapero: *Prescribing for the Patients Needs*, Dr. Harry Jolliffe, and *The Visual Fields in Glaucoma, Testing, Recognition and Referral*, Dr. Harry Bloom and Dr. Melvin Nadell. Four units of post-graduate credit are available for this session which includes 64 hours of lecture and demonstration. The tuition fee is $120. Further information may be obtained by writing Dr. Frank A. Brazelton, Los Angeles College of Optometry, 950 West Jefferson Boulevard, Los Angeles 7, California.

# LINES OF CONSTANT HUE IN THE BLUE CORNER OF THE COLOR MIXTURE DIAGRAM*

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## INTRODUCTION

In 1954 Fry[1] reported that the blue corner of the color mixture diagram was dichromatic and conjectured that isochromatic lines in this zone may be extensions of the lines of constant hue in the trichromatic region of the diagram. The present study has been undertaken to determine how the isochromatic lines in the dichromatic zone are related to the lines of constant hue in the trichromatic zone.

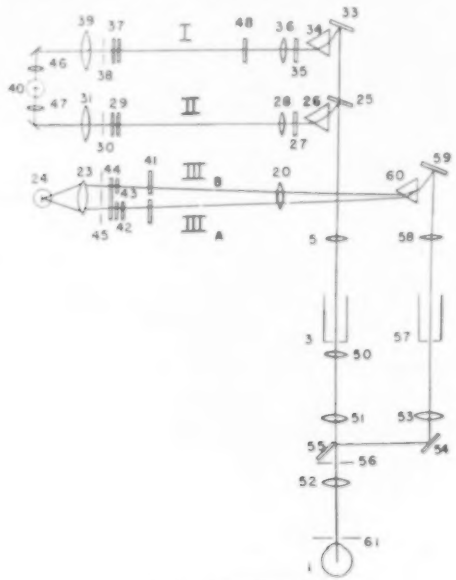


Fig. 1. Apparatus.

*This paper is based upon a thesis submitted by the senior author for the M.Sc. degree on Physiological Optics at the Ohio State University. The junior author served as the advisor. Submitted on October 1, 1958, for publication in the April, 1959, issue of the AMERICAN JOURNAL OF OPTOMETRY AND ARCHIVES OF AMERICAN ACADEMY OF OPTOMETRY.

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APPARATUS

The instrument used in this investigation was a colorimeter designed by Fry.[2] It is schematically illustrated in Figure 1 and consists of three monochromators utilizing 60° constant deviation type prisms with Wadsworth mountings for dispersing systems. These monochromators are referred to as Systems I, II and III and are so designated in Figure 1. The procedure for calibrating the dispersing systems for wavelength has been previously described by Fry.[2] The bipartite field of view is shown in Figure 2. The boundary of this field is the edge

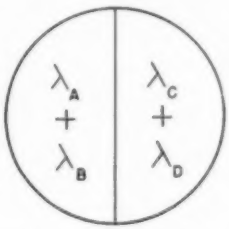



Fig. 2. Bipartite Stimulus which Substends a Visual Angle of 2.34°.

of aperture (56) and the dividing line between the two halves is the edge of the mirror (55). $\lambda_D$ is from System I, $\lambda_C$ from System II, $\lambda_B$ from System $III_B$ and $\lambda_A$ from System $III_A$. The right half of this field composed of a mixture of $\lambda_D$ and $\lambda_C$ is formed as follows. A ribbon filament lamp (40) constitutes the source. The beam from System I is reflected by the first surface mirror (33) and transmitted through a plate of glass (25). This plate of glass (25) reflects the beam from System II and thus mixes the beams from Systems I and II.

Entrance slits for Systems I and II are (38) and (30). The numbers (37) and (29) represent crossed polaroids which control the luminance values and are synchronized so that the transmittance of one increases as that of the other decreases and the sum of the two transmittance values remains constant. Source (40) can also be controlled, when necessary, with a variac. Two colored filters, (35) and (27), screen out unwanted parts of the spectra. Lenses (46), (39) and (36) form an enlarged image of the ribbon filament (40) on the face of the prism (34). Lenses (47), (31) and (28) play a similar role in System II. The polaroid (48) can be adjusted so that the two beams from source (40) are equal when the crossed polaroids (37 and 29) are set so that each gives a transmittance of 0.5. When this condition is fulfilled the retinal illuminance produced by the combined beams from Systems I and II remains constant as the ratio of the two beams

changes. The combined beam from Systems I and II is transmitted through lens (5), slit (3), lenses (50) and (51), and through the right half of aperture (56).

System III is formed as follows: Two slits (45) provide two separate beams ($\lambda_A$ and $\lambda_B$) from source (24). Numerous pairs of slits were available. Two colored filters (41) screen out stray light from the unused parts of the spectra. Two fixed polaroids (43) have their axes oriented at right angles so that as polaroid filter (44) rotates one beam increases in amount as the other decreases and the sum of the two transmittance values remains constant. Rotating polaroid filter (42) covers only the beam IIIA and gives an independent control of the retinal illuminance produced by this component. When this was properly adjusted the retinal illuminance produced by the combined beam was constant regardless of the ratio of the two components. The output of source (24) can also be controlled with a variac.

The two beams from System III after passing through dispersing prism (60) are combined into a mixed beam which is reflected by the first surface mirror (59) through lens (58), slit (57) and lens (53) and is reflected again by the first surface mirrors (54) and (55) through the left half of the aperture (56).

Lenses (50), (51), (53) and (52) make the exit slits (3) and (57) conjugate to the circular aperture (61). The images of the exit slits are centered in the aperture (61) which is 2.9 mm. in diameter. An emmetrope has to use approximately 2.00 diopters of accommodation to focus on the edge of the aperture (56).

## PROCEDURE AND RESULTS

Each phase of this investigation was carried out on two observers, G.A.F. and R.J.B. Essentially the same results were obtained with both observers. Throughout the entire investigation an attempt was made to maintain a constant level of retinal illuminance for the stimuli (221 trolands). This eliminated any effects of the Zezold-Brücke phenomenon.

The first phase of the study consisted in obtaining data for locating the spectrally pure stimuli on a color mixture diagram. 674 $m\mu$, 520 $m\mu$ and 468 $m\mu$ were selected as primaries for the diagram.

A 486.8 $m\mu$ stimulus was introduced into the right half of the field for System II. The polaroids (37) and (29) were adjusted to give beam II a transmittance of 1.0 and beam I a transmittance of zero and the variac was adjusted to give a retinal illuminance of 221 trolands. In making this setting the brightness of the 486.8 $m\mu$ stimulus was compared to the brightness of a white stimulus in the left half

of the bipartite field which was introduced by placing a white surface of known luminance between (57) and (53).

A 674 mμ stimulus was then introduced into the right half of the bipartite field from System I and equated to the 486.8 mμ stimulus by adjusting polaroid (48) when polaroids (37) and (29) were set to give equal transmittance in the two systems. Flicker photometry was used to make the match between the two beams. A rotating sectored disk of variable speed was mounted in front of the polaroid filters (37) and (29) to alternate the two beams.

The next step in the procedure was to select and place at (45) a pair of slits which introduced 486.8 and 674 mμ into the left hand of the bipartite field when the mirror-prism unit (60 and 59) was rotated to the proper setting. The polaroid (42) and the variac controlling the source (24) were adjusted to make each of the two stimuli produce a maximal retinal illuminance of 221 trolands. This was achieved by comparing the cyan in System IIIA with the cyan in System II and the red in System IIIB with the red in System I.

A new pair of slits was selected which yielded 468 mμ and 520 mμ when the mirror-prism unit was rotated to the proper setting. It was determined how to adjust the polaroid (42) and the variac controlling the source (24) to make each of these two stimuli produce a maximum retinal illuminance of 221 trolands. In this case both 468 mμ in System IIIA and 520 mμ in System IIIB had to be compared directly with 486.8 in System II.

It was then possible to reset the mirror-prism unit (25 and 26) in System II to give first 468 mμ and then 520 and 674 mμ. In each case it was determined how to set the variac controlling (40) to give System II a maximum luminance of 221 trolands. This was achieved by comparing stimuli in System II with the corresponding stimuli in System III.

Finally it was determined how to adjust the polaroid (42) and the variac controlling source (24) to make Systems IIIA and IIIB each yield a maximum retinal illuminance of 221 trolands. when slits were used which gave a combination of 520 mμ and 674 mμ and also when another pair of slits was used which gave a combination of 468 mμ and 674 mμ.

By way of summary it may be said that the above procedure made it possible to obtain mixtures of various pairs of stimuli in System III which had a constant retinal illuminance and which could be compared to a combination of any monochromatic stimulus in System

I with a depurifying stimulus in System II (674 mμ, 520 mμ or 468 mμ).

The acquisition of color mixture data was split into three phases corresponding to three parts of the spectrum. For the region between 520 mμ and 674 mμ $\lambda_A$ was set at 674 mμ and $\lambda_B$ at 520 mμ. $\lambda_D$ was varied in 10 mμ steps between 520 mμ and 674 mμ and the relative proportions of $\lambda_A$ and $\lambda_B$ necessary to obtain an exact match were determined. It was found that a depurifying blue did not need to be added to $\lambda_D$ so $\lambda_C$ was not utilized. A brightness match was obtained in each case by varying polaroid (48). The results are shown in Figure 3.

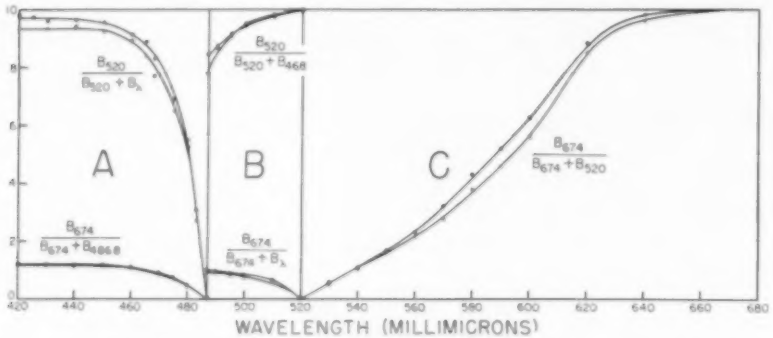



Fig. 3. Color Mixture Data for the Spectrally Pure Stimuli.

For the region between 486.8 mμ and 520 mμ, $\lambda_A$ was set at 520 mμ and $\lambda_B$ at 468 mμ. $\lambda_C$ set at 674 mμ was utilized as a depurifying stimulus for $\lambda_D$. $\lambda_D$ was set at a number of wavelengths between 486.8 mμ and 520 mμ and for each the percentage of $\lambda_A$ and $\lambda_B$ and the necessary percentage of depurifying $\lambda_C$ to obtain an exact match were determined. The brightness match was made by varying the polaroid (48). The results are shown in Figure 3. For the region from 485 mμ down to 420 mμ $\lambda_A$ was set at 674 mμ. $\lambda_B$ at 486.8 mμ and the depurifying stimulus $\lambda_C$ at 520 mμ. Again the relative proportions of the four stimuli were determined to give exact matches an $\lambda_D$ settings between 486.8 mμ and 420 mμ. The results are shown in Figure 3.

The data in Figure 3B and Figure 3C were converted directly to terms of r and g.

$$r = \frac{B_{674}}{B_{674} + B_{520} + B_{468}} \text{ and } g = \frac{B_{520}}{B_{674} + B_{520} + B_{468}}.$$

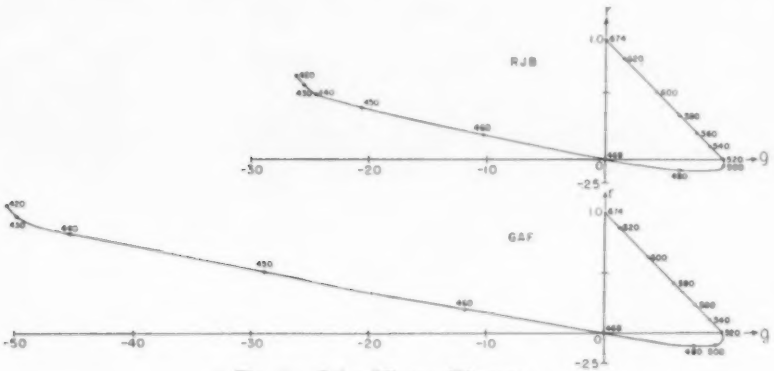



Fig. 4. Color Mixture Diagrams.

Since the data in Figure 3A were expressed in terms of the primaries 674 mμ, 520 mμ and 486.8 mμ it was necessary to develop transformation equations to convert the data to terms of 468 mμ, 520 mμ and 674 mμ. This was done and Figure 4 shows a plot of all the color mixture data in terms of r and g.

It was found that the type of graph shown in Figure 4 was not entirely satisfactory and a new set of primaries, involving 674 mμ, 468 mμ and an imaginary green stimulus was selected for the final display in Figures 9, 10, 11 and 12.

The experimental determination of the lines of constant hue was made in two separate approaches. One was based on lines converging at 468 mμ and the other on lines converging at 674 mμ.

TABLE I

Pairs of Spectral Stimuli Employed to Trace Lines of Constant Hue

| Pairs of stimuli for lines converging on 468 mμ | | Pairs of stimuli for lines converging on 674 mμ | |
|---|---|---|---|
| 468 | 622 | 674 | 493 |
| | 605 | | 490 |
| | 593.2 | | 486.8 |
| | 580 | | 483 |
| | 575 | | 480 |
| | 565 | | 468 |
| | 546 | | 450 |
| | 520 | | |

Colors along each of these lines were obtained by mixing a pair of spectrally pure stimuli. The pairs of stimuli employed are shown in Table I. The apparatus made it possible to compare a mixture of two stimuli from Systems I and II with a mixture of two stimuli from

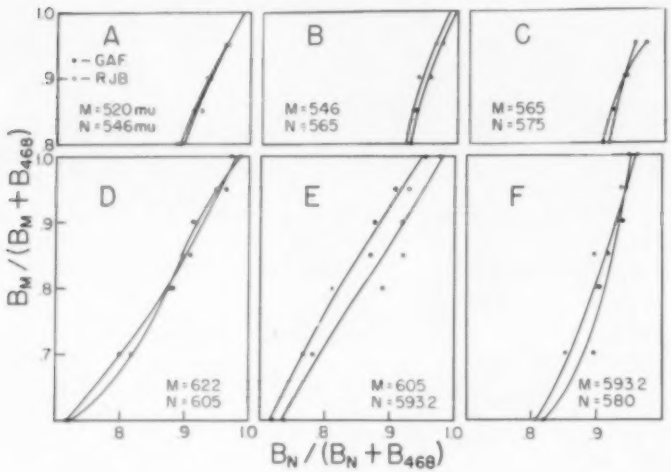



Fig. 5. Hue Matches for Pairs of Lines Converging on 468 mμ.

Systems IIIA and IIIB. It was also possible to change the mixtures without changing the retinal illuminance which was constant at 221 trolands. Subject R.J.B. adjusted the controls which determined the maximal values of the reinal illuminance and it was not necessary to readjust these controls for G.A.F. because the mixtures which were equal in brightness to R.J.B. were also equal to G.A.F. A constant maximum value of 221 trolands was maintained by comparing 605 mμ with 622 mμ, 693.2 mμ with 605 mμ and 580 mμ with 693.2 mμ. Then starting with 520 mμ, 546 mμ was compared with 520 mμ, 565 mμ with 546 mμ and 575 mμ with 565 mμ. Starting again with 468 mμ, 450 mμ and 480 mμ were compared with 468 mμ, 486.8 mμ with 480 mμ and 483.5 mμ, 490 mμ and 493 mμ with 486.8 mμ.

Figures 5 and 6 show the mixtures on adjacent lines which match in hue. Each point is an average of five settings. In the case of each pair of lines one lies closer to the achromatic point than the other. The mixture on this line was varied while the mixture on the other was kept fixed.

Various monochromatic spectral stimuli between 485 mμ and 520 mμ were compared with mixtures of 520 mμ and 468 mμ to determine what mixtures would match the spectrally pure stimuli in hue. The results are shown in Figure 7.

Furthermore various monochromatic stimuli between 478 mμ

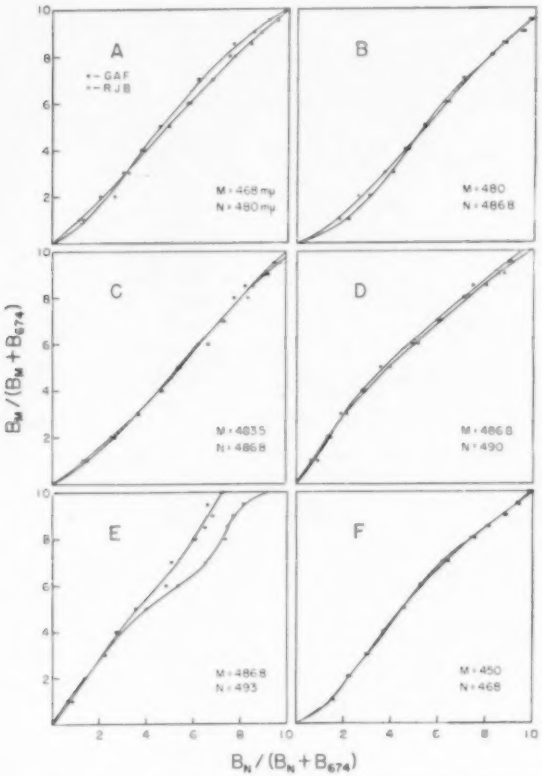


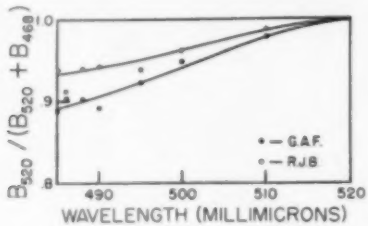

Fig. 6. Hue Matches for Pairs of Lines Converging on 674 mμ.

and 468 mμ were compared with mixtures of 468 mμ and 674 mμ to determine what mixtures would match the spectrally pure stimuli in hue and saturation. The results are shown in Figure 8.

These data can be used to trace lines of constant hue from the achromatic point to the spectrum locus, or the line connecting the two ends of the spectrum locus in the case of the purple hues. This has been done and the results are shown in Figures 9, 10 and 11. Figures 10 and 11 include a hue match between a 622 mμ — 468 mμ mixture and the monochromatic stimulus 674 mμ.

## CONCLUSIONS

Several important observations can be noted from Figures 9, 10 and 11. First, as one might expect, all of the lines of constant hue converge to an achromatic point.



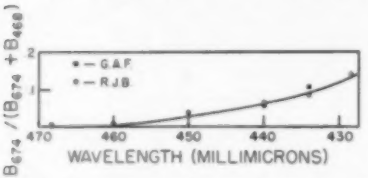




Fig. 7. Top. Hue Matches between a Mixture of 485 $m\mu$ + 520 $m\mu$ and Monochromatic Stimuli from 485 $m\mu$ to 520 $m\mu$.
Fig. 8. Bottom. Hue Matches between a Mixture of 468 $m\mu$ + 674 $m\mu$ and Monochromatic Stimuli from 428 to 468 $m\mu$.

All of these constant hue lines in the blue corner of the diagram are nearly parallel the spectrum focus up to a point corresponding to about 490 $m\mu$. Then they make a sharp bend and converge toward the achromatic point.

Fry's finding that the blue corner of the color mixture diagram is dichromatic has been confirmed. During this experiment the retinal

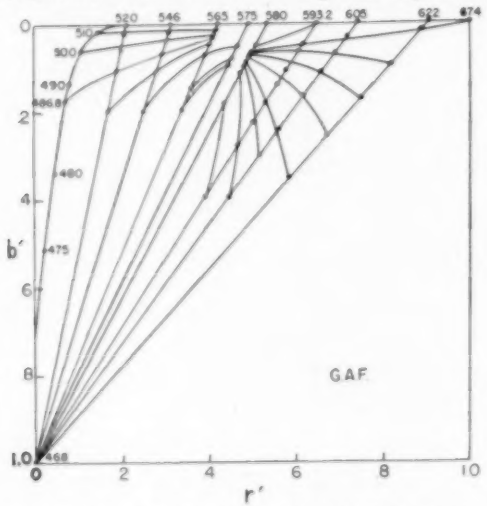



Fig. 9. Lines of Constant Hue Based on Pairs of Lines Converging at 468 $m\mu$.

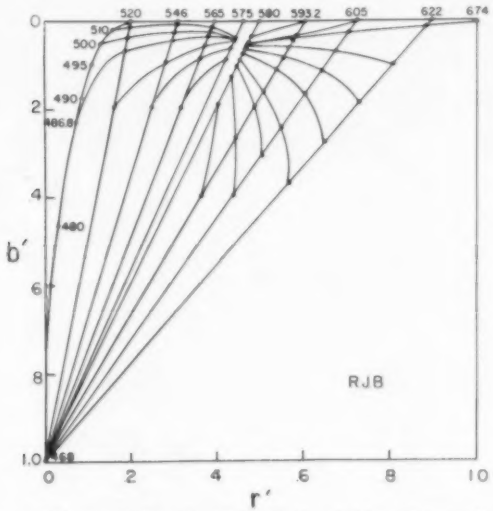



Fig. 10. Lines of Constant Hue Based on Pairs of Lines Converging at 468 mμ.

illuminance of all stimuli was kept at a constant level of 221 trolands. Matches between mixtures of 450 mμ — 674 mμ and 468 mμ — 674 mμ involving less than forty per cent of 674 mμ constituted matches in saturation as well as hue. The same thing applies to matches between mixtures of 468 mμ — 674 mμ and 480 mμ — 674 mμ at the blue side of the diagram.

The fact that the blue corner of the color mixture diagram is dichromatic, makes it unsatisfactory to use a blue in the range from 420 mμ to 480 mμ as one of the primaries in a tristimulus colorimeter. This is true because different mixtures of say 460 mμ and 680 mμ can be found which will match different mixtures of 520 mμ and 430 mμ. The match is not unique.

One can cope with this problem by using stimuli such as 486.8 mμ, 520 mμ and 674 mμ as has been done in this study. There is only one mixture of 486.8 mμ and 674 mμ which can be matched by a mixture 520 mμ and a given color at the blue end of the spectrum. However, as can be seen in Figure 4 the extreme blue end of the spectrum locus lies at a considerable distance from the line connecting 486.7 mμ and 674 mμ and consequently one cannot expect any great degree of precision in locating these colors.

It is proposed, however, that use can be made of information about lines of constant hue to locate these colors more precisely.

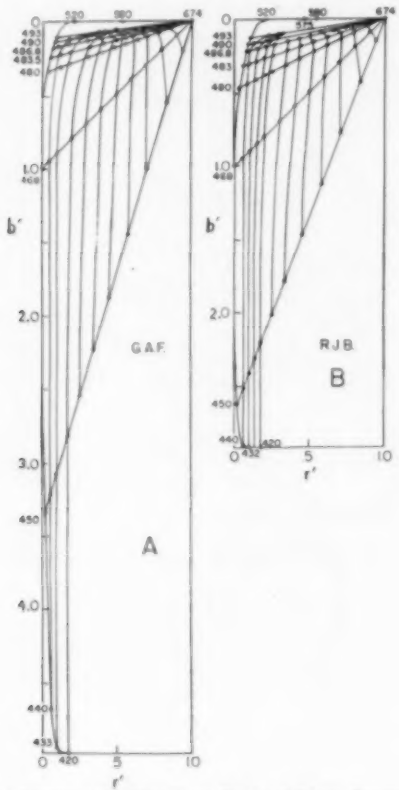



Fig. 11. Lines of Constant Hue Based on Pairs of Lines Converging at 674 mμ.

Since the spectrally pure stimuli between 460 mμ and 475 mμ have the same hue and saturation when they are made equal in brightness, it may be assumed that they must fall on a straight line on the mixture diagram. This merely means that the curves selected to fit the data between 460 mμ and 475 mμ in Figure 3A must conform to a straight line in Figure 4.

Furthermore one can match any color below 450 mμ on the wavelength scale with a mixture of 450 mμ and 674 mμ and then assume that the color in question must lie on a line through the mixture which is parallel to a line tangent to the spectrum locus at 465 mμ. This helps to determine the form of the curves selected to fit the mixture data for wavelengths below 450 mμ.

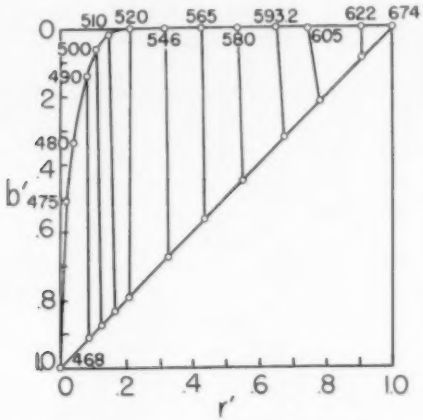



Fig. 12. Wright's Color Mixture Data for an Average Tritanope Plotted on the Color Mixture Diagram in Figure 9.

This was the procedure used in selecting the curves to fit the data in Figure 3A. The relation between the spectrum locus and the lines of constant hue is shown in Figure 11.

Wright[3] has determined for an average tritanope the mixtures of 480 m$\mu$ and 650 m$\mu$ which will match the various spectrally pure stimuli. From this data one can compute the mixtures of 468 m$\mu$ and 674 m$\mu$ which will match the various spectrally pure stimuli and these mixtures have been plotted in Figure 12 on the color mixture diagrams for G.A.F. If Figure 12 is compared with Figure 11A it may be deduced that the isochromatic lines in the dichromatic zone of a normal observer correspond to the confusion lines of a tritanope.

By preadapting the eye to a chromatic stimulus, a color on the opposite side of the mixture diagram may be perceived as supersaturated. According to the Young-Helmholtz theory all possible colors including the supersaturated colors must be inclosed by a triangle, but according to the concept advocated by Fry[4] these colors may be bounded by a quadrilateral.

Since the confusion lines of the deuteranope may be assumed to converge at the point ($x = 1$; $y = 0$) on the ICI chromaticity diagram,[5] it follows from this that they must be parallel to the r′ axis in Figure 12. Since this is true and since the confusion lines of the tritanope may be assumed to be parallel to the b′ axis, it may be argued that the color mixture polygon is a quadrilateral with its four corners corresponding to the four corners of each of the diagrams in Figure 11.

According to this scheme of things the lines tangent to the spectrum locus 465 $m\mu$ and at the red end represent adjacent legs of the quadrilateral instead of opposite legs as previously proposed by Fry.

The argument that they represent opposite legs was based upon the finding that the fundamental green stimulus falls on the $\lambda'$ axis at $r' = 0.16$. Consequently it was argued that there must be an intermediate leg between those tangent to the spectrum locus in the blue and red regions. This discrepancy has not been resolved.

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## ANNOUNCEMENT

### CONTACT LENS FITTING COURSES AT HOUSTON

The Texas Academy of Optometry is offering a series of three day post-graduate courses in contact lens fitting at the College of Optometry, University of Houston, Houston, Texas. This series of courses will be given and repeated on the following weekends.

| | |
|---|---|
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| June 6, 7 and 8. | June 13, 14 and 15. |
| July 11, 12 and 13. | July 25, 26 and 27. |

Each course will begin with the most elementary ideas of contact lens fitting and proceed to the more advanced concepts. The course is designed for the beginner to give him the necessary background to start fitting contact lenses. This group of courses will be taught by Dr. Bernard Mazow, Houston, who is a diplomate of the Contact Lens Section of the Academy, a lecturer in Optometry and director of the Contact Lens Clinic at the College. These courses meet the standards of post-graduate study required by many States. Enrollment will be limited to eight optometrists in any one course. The tuition is $100 and full payment must be made with your letter of registration. Checks should be made payable to the Texas Academy of Optometry, 4118 Fannin Street, Houston, Texas.

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## ON THE SATISFACTION THAT COMES TO OPTOMETRISTS

Most optometrists in the United States are familiar with the life history of Theodore Roosevelt. When reading of his boyhood they have been moved at his inability to see well and experienced a thrill when the discovery was accidentally made by his father that young Teddy had a serious visual problem. They rejoiced, too, at the difference it made in the boy's life when his myopia and astigmatism were corrected by means of spectacles.

To be sure, similar experiences occur frequently in busy optometric practices where patients literally enter new worlds through the magic gates of ophthalmic lenses. Yet these many splendid experiences are for the most part locked up in the hearts and minds of the participants, as these events rarely become public knowledge.

Another world renowned figure, His Highness, The Aga Kahn, Iman of the Ismailis, had a more or less similar experience. He tells*

*His Highness, The Aga Kahn. The Momoirs of Aga Kahn. Simon and Schuster, New York City. 1954.

us that as a boy in Bombay, India, his reading and whole outlook on life were permanently transformed by a small, wise decision. Much that had hitherto been pain and hardship became pleasure and delight. His health was immediately improved and he was saved much trouble and misfortune in later life. What happened was, that his third and last tutor had at one time been employed by an optometrist of that day. This was around the year 1890. As soon as the little prince settled down to work the tutor realized how terrible—and how dangerous—was his congenital myopia.

The tutor insisted on taking the little prince to the optometrist whose employee he had been: he had the little fellows eyes tested and had him fitted with proper spectacles both for reading and distance. The princes uncles strove to interfere, but the tutor was adamant: he carried with him the prestige of the West, and he won the day. Sixty years later His Highness, The Aga Kahn, says, "This sensible and kindly action saved me infinite pain and worry, and gave me a new world in which to live."

In the book the author describes the ignorance on these matters that was then prevalent among those who surrounded him. He continues, "It is strange and sad to recall that already, more than once before the tutors arrival, I had in fun picked up and put on a pair of spectacles left lying about by one of our family or friends. The moment I put them on I discovered the joy of a new and exciting world: a world of human beings of definite and different shapes, a world of green trees and brightly colored flowers, and of sharp, strong light instead of the perpetual haze and fog, the world blurred at the edges, which was all that an extremely myopic little boy could see. But these minutes of joy were of short duration, and were indeed forbidden, for the servants had orders to take the spectacles away from me, since my family could not believe that a child could be short-sighted and thought that I was being self-indulgent and silly." But, as has been said, the British tutor changed everything and the boy was given good useful vision.

Reports such as these highlight the work of optometrists. They bring to them a great measure of satisfaction that through their skills so much help and pleasure may be given their patients. It makes them realize, too, that while great progress has been made in eliminating the public ignorance which exists on these matters, that there is yet much more to be done. Even today there are children in all parts of the world needing and wishing for, the professional help the optometrist may bring to them.

CAREL C. KOCH

SPECIAL REPORT

# VISION AND LEARNING*

Thomas H. Eames†
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Boston, Massachusetts

The child's desire for learning is taken for granted but actually there are wide individual differences in how much children value it. They range from outright rejection of learning to a passion for it.

Learning occurs in the brain. There are several theories about the nature of the change that learning produces, including such things as a possible rearrangement of the protoplasm of the brain cells, electrochemical changes, variations in electrical potential, resonance, comparable to that met in electronics, and the like. Regardless of what the explanation is, the fact remains that we do not know its nature, but we know that *some* change occurs which makes memory possible. Orton named the changes "Engrams" which enables us to talk about them conveniently although we still do not comprehend their nature.

When these changes or memory traces are laid down in learning they come about as a result of perceptions made by the learner. He knows nothing of the world outside of himself except as he perceives it. Objects and situations in his environment stimulate his sensory receptors and they transmit nerve impulses to his brain over one or more of the various sensory channels of sight, hearing, taste, touch and smell. Perception is unique for each individual and his knowledge of the thing or situation that gave rise to it varies with his past learning, concepts and mental set.

Visual perception is not the same as seeing. Although normal people receive relatively similar retinal images of objects or symbols, they do not necessarily perceive identically, since perception is a psychological and subjective act. There are individual differences in perception. One man sees a log, another a piece of oak and a third a potential door frame.

Perceiving is not the same as learning. A person can perceive but not learn or retain. According to the old cliche, "It goes in one ear

*Read before the Annual Round-Table Dinner of the American Academy of Optometry, Boston, Massachusetts, December 15, 1958. For publication in the April, 1959, issue of the AMERICAN JOURNAL OF OPTOMETRY AND ARCHIVES OF AMERICAN ACADEMY OF OPTOMETRY.
†Ed.M., O.D., M.D. Member of faculty.

and out the other." The same is true of vision and all the other senses. If a thing is to be learned it must be acted upon as well as perceived. The learner must *respond* to the perception with attention and consideration. Not only must he see or hear, but he must also *think* about the new information, *relate* it to his previous experiences and *speculate* on where and how he may be able to use it.

Academic learning comes mainly through the eyes and ears. The ears bring sensory impressions of oral explanations, discussions and lectures, while the eyes present for perception impressions of observations, demonstrations and texts. At least half of learning comes to the brain over visual channels which makes it of particular interest to the eye man. The ophthalmologist and optometrist concern themselves with visual perception and try to bring it to its highest perfection in order to allow the brain to receive adequate impressions of learning materials and other objects in the environment. The teacher is also interested in visual perception to the extent that she wishes to know that the pupil has an adequate degree of this psychological skill to enable him to receive and act upon perceptions of material presented visually for learning. She also wishes to locate those with inadequate visual perception and bring them to the attention of parents and doctors so that their sensory deficiencies may be corrected or raised to more adequate levels.

Many people learn equally well when material is presented through either visual or auditory channels and teaching usually presupposes about equal skill in an average pupil. There are many learners in whom one perceptual mechanism is more able than the other. One child may learn better through visual presentation, while another learns more effectively when he hears the material rather than sees it. Teaching can be adapted to either type of learner.

When visual perception is good and auditory poor, a child learning to read will have trouble with oral explanations and sounding out new and unfamiliar words, but he will be able to learn more easily if the material is presented through a visual method, such as the building of an adequate sight vocabulary. This consists of a stock of words which the child learns to recognize by general shape rather than by their component phonograms. A pupil with the opposite condition in which visual perception is poor and auditory good, will do less well with the visual method but is likely to profit more fully from a hearing approach, emphasizing, for example, oral instruction and the sounding out of new words.

Poor visual perception is not necessarily due to low visual acuity.

While poor vision may result in poor visual perception, some children whose eyes are extremely faulty and whose vision is low have a high degree of this perceptual skill. The same is true of auditory acuity. Children with poor hearing may have either good or bad auditory perception. This is because the eyes and ears are only receptor organs for the respective senses. Perception occurs in the brain; not in the eyes or ears. Many people learn to interpret and therefore perceive with reasonable accuracy the relatively imperfect sensory messages sent in by these peripheral receptors.

The doctor properly corrects all ocular handicaps to raise the child's potential for visual perception to its maximum. The teacher is often the first to detect the presence of poor visual or auditory perceptual ability and suggests professional examination. After the child returns from the doctor she observes whether or not there is residual perceptual inadequacy and shifts to an appropriate type of presentation in keeping with the perceptual abilities of the pupil. Sometimes the doctor's best efforts, which perhaps raise visual acuity or eliminate some source of eye strain, make no impression on visual perception or may even make it worse. Corrective lenses cut down the speed of visual perception in some cases. It is always a good plan to check this when spectacles are being considered for a school child with learning difficulties and refrain from prescribing these if they impair the capacity for visual perception. Only the occasional case exhibits this. More commonly visual perception is either unchanged or improved by adequate correction of refraction.

When visual perception remains poor the teacher properly uses "eye training." This is neither ophthalmic nor medical but pedagogical. The teacher shows the child what to look for. She teaches him good habits of perception. She impresses him with the fact that there is much to see that he is missing. She tries to make him vision conscious through practice with pictures, shapes, word forms and sentences. She devises many ingenious games for the younger child which teach him to look at things more discriminatingly and to "see" them in a more complete perceptual sense. There are also techniques for "ear training," which is comparable but directed to hearing all that there is to hear rather than only a part of it.

The child with poor visual perception is unobservant and uncritical. He has trouble in learning and does not retain what he learns. He finds it difficult to handle likenesses and differences, often confusing words of similar form in reading such as they, them, there, these and those. He develops sight vocabulary very slowly and finds it hard to

generalize or transfer his learning from one problem situation to another. If his auditory perception is better than his visual perception he will learn better with a sounding approach, as discussed in an earlier paragraph.

Some doctors are becoming interested in learning problems. They are investigating the school situation in their communities, modern methods of teaching, the nature and duration of study assignments and the point of view of teachers. Some of the doctors are taking courses in education, the better to understand learning problems that come to them as eye cases. They are employing short exposure and pacing exercises in their orthoptic work: the same techniques that teachers use for similar purposes quite legitimately, since they are essentially teaching devices. The best approach is to correlate the daily school work with these exercises, such as using the history assignment in the pacing device and the spelling words in the tachistoscope. Words from the daily reading or spelling lesson and review words from the previous week form an adequate list for this work. By doing this, one teaches for direct learning of the skills being practiced and reenforces school learning at the same time. The use of arbitrarily chosen digit or word lists is to be depending too much on transfer, which is generally regarded as less efficient than direct learning.

Close cooperation between doctor and teachers is highly desirable. Neither knows much about the other's field unless he has special experience or training in it as well as in his own. Both can give the other helpful information that is very much worth while. The doctor can give the teacher advice as to the amount of use of the eyes in a given case, how much spectacles are to be worn and for what tasks, the length of assignments likely to be performed without impairment of eye function or condition, seating placement and the length of practice periods. The teacher can detect eye conditions that may not show on routine eye examination, such as those exhibiting symptoms and signs only after long periods of close application. She sees the child five hours a day, five days a week, while the doctor often sees the patient only during a regular appointment period of one hour or less—occasionally more, but still not for as long a time as the teacher does. Most children come to the doctor when rested and subtle difficulties may be masked by accommodative, convergent or other compensations. The teacher sees the same child during all stages of tiring from complete rest to marked fatigue. Her observations are valuable.

Some hypermetropic children and others with accommodative insufficiency from that or other causes may not exhibit test responses

consistent with the prescription of spectacles, but if the teacher has reported signs of eye strain after close work or toward the end of the school day, a pair of +0.50 D. spheres, given temporarily for book and desk work, may afford the child a great deal of comfort. They may increase his effective learning time by reducing the eye tension under which he performs close work.

Most teachers are willing and anxious to discuss their pupils' eye condition with the doctor. The man who will take the time to do this will gain helpful information about his patient, will do himself immense personal good and will be building the best kind of public relations for his profession.

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## CURRENT COMMENTS

Terry Judith Parkins
Editorial Assistant

Optometrists will confer a favor by sending news items of general interest for this department; such as relate to new instruments, clinical techniques, education, visual health and optometric legislation and organization.

### DALLAS MEETING OF THE A.O.A. IN JUNE

At the end of June the American Optometric Association will hold its 62nd convention at the Statler-Hilton hotel in Dallas, Texas. The convention dates are June 28, 29, 30 and July 1. The convention is so timed as to enable optometrists who wish to drive to the meeting with their families to utilize the July 4 holiday weekend which follows the convention.

The Texas Optometric Association will be hosts to all A.O.A. member optometrists. They will be on hand in full force to see to it that visitors are given a fine, rousing Texas welcome. These Texas people know how to do such things. In very large part most Texas men, including Texas optometrists, are still boys at heart and have never gotten over the idea that herding cattle is *the* one really outstanding male vocation. So when you come to Dallas, be prepared to find your hosts in wide brim Stetsons, riding boots and perhaps toting a six gun. But whatever they wear, you can be sure it will be accompanied by a broad smile of welcome.

The convention will be arranged around four main events. These are the meeting of the A.O.A. House of Delegates; the exhibits of manufacturers; the banquet and the educational program.

During the educational sessions Dr. Neal J. Bailey and Dr. John C. Neill will give two separate eight-hour demonstration periods on

"Contact Lenses." Dr. Alfred Rosenbloom and Dr. Vincent Ellerbrock also will collaborate in a course on "Aids for the Partially Blind." Dr. Frederick Kushner will conduct the special "Practice Management" course, and Dr. Merrill J. Allen will lecture on "Refractive Technique." These courses will each be given two times during the convention.

The program for the Section on Military Optometry will highlight a panel discussion on "Factors in Developing a Minimum Optometric Examination Routine for the Military," with panelists from all branches of the service. A special "Symposium: Medical Service Corps Trends" will feature Colonel L. P. Zagelow, chief, Medical Service Corps, U. S. Air Force; Colonel Bernard Aabel, chief, Medical Service Corps, U. S. Army; and Captain Leo J. Elsasser, chief, Medical Service Corps, U. S. Navy. Rounding out the military program will be A.O.A. counsel Harold Kohn speaking on "Malpractice Implications for the Military Optometrist"; Dr. Lester H. Sugarman discussing "Advantages of Membership for the Military Optometrist"; and Dr. G. N. Getman lecturing on "The Development of Binocularity." The program concludes with a "Report of Contact Lens Research" by Major Floyd M. Morris, USAF (MSC), of the School of Aviation Medicine at Randolph Air Force Base, Texas.

Dr. Chester H. Pheiffer, Houston, president of the Texas Academy of Optometry, is in charge of the informal Academy luncheon for all members and guests at the A.O.A. meeting. This special luncheon will be held at noon on Tuesday, June 30, at the Statler-Hilton. Dr. Lawrence Fitch, president of the American Academy of Optometry, will speak, and all Academy members and their families are expected to attend. Members are especially urged to bring guests.

This convention is recommended as the focal point for a light spirited 10 day summer vacation. Pile the family into the car and drive to Dallas. You will enjoy your cross country travel on fine roads and you will meet loads of friendly optometrists from everywhere at the 62nd meeting of the A.O.A. Dr. O. Reynolds Young, Dallas, chairman of the A.O.A. entertainment committee, has promised all optometrists a fine time in the heart of the mid-continent oil fields.

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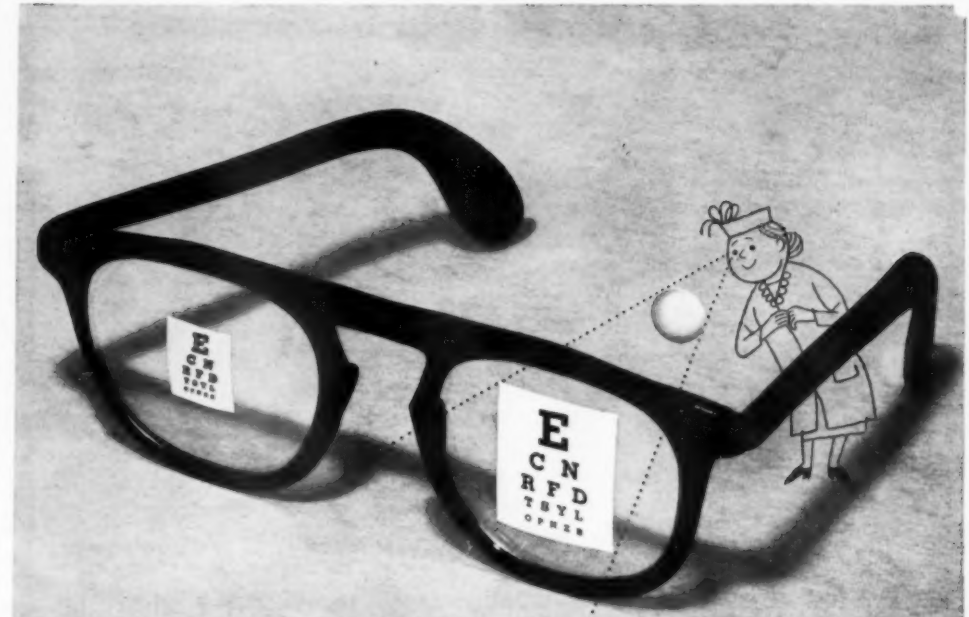

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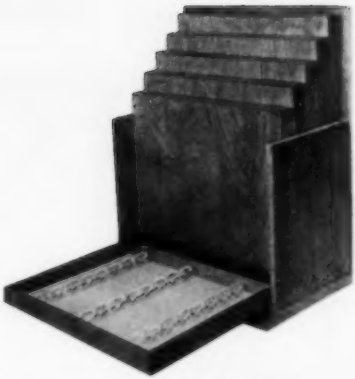

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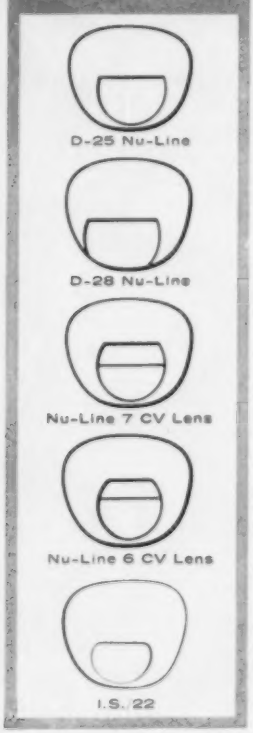


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The new Younger-22 Seamless Lens is the first truly-invisible, optical-quality, dual-field lens. Not only is the segment invisible to the beholder; the wearer is not likely to be annoyed by the visible segment line; the soft transition zone between fields eliminates that.

Your presbyopic patients will welcome this ageless dual-field lens; convince yourself by trying a pair at your first opportunity!

## The *New* YOUNGER-22 Seamless Lens

YOUR PATIENT TAKES NO RISK with Younger-22s. If the patient cannot wear them for any reason, it will be replaced with a fused bifocal of your choice at no additional cost.

*Frame shown: Liberty's famous Broker 215*

2. Front surface quality and spherical accuracy to millionths of an inch.

3. Soft transition, greater comfort and less 'bifocal shock' than a fused segment line.

1. 22mm usable segment with power deviation less than .05 diopters (4 Newton rings) — 40% more precise than industry standards.

4. Segment and transition size deviation less than .0125mm, with no chromatic aberration—color-free.

**YOUNGER**
Los Angeles 15, California